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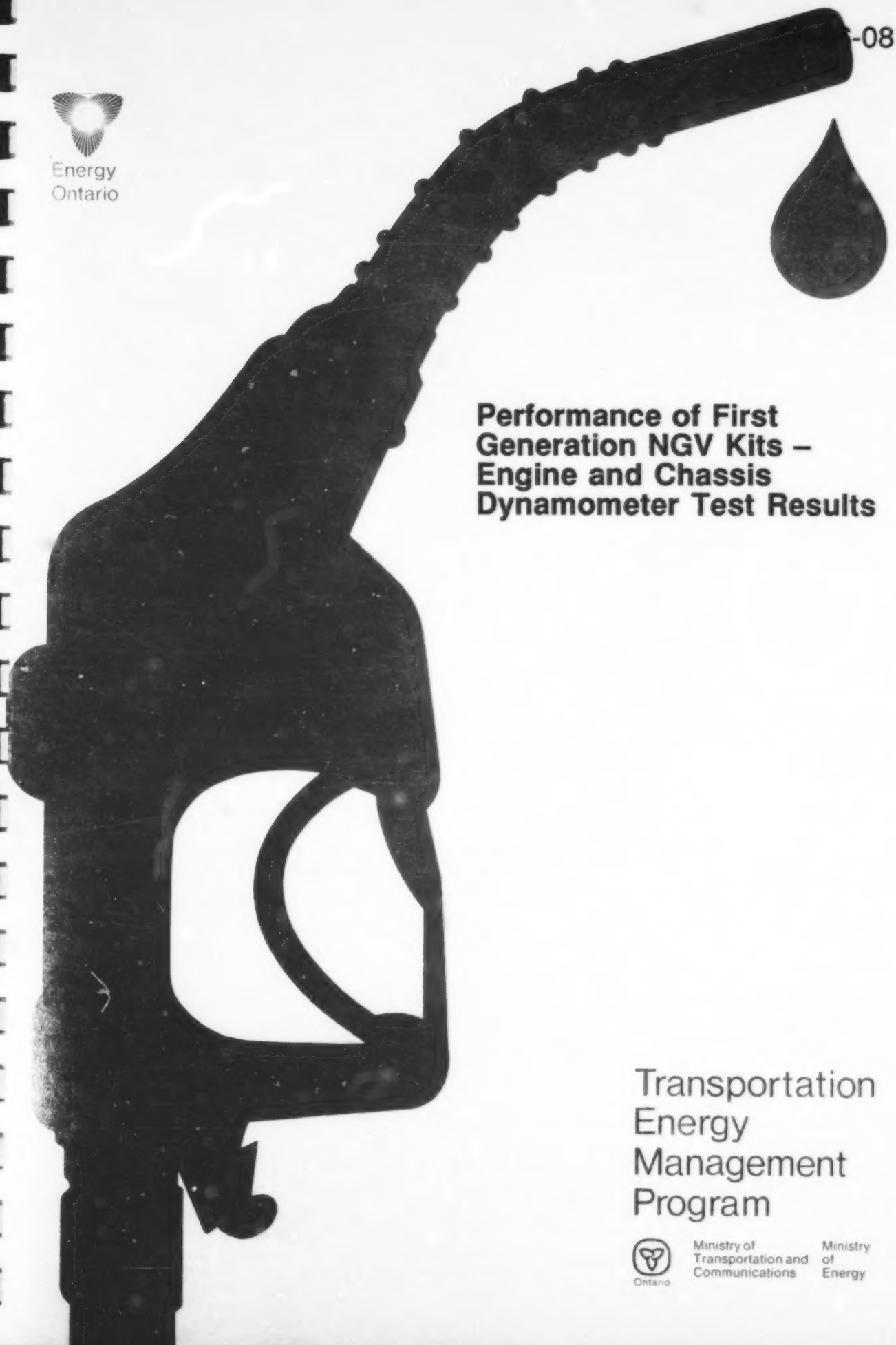

Performance of First Generation NGV Kits – Engine and Chassis Dynamometer Test Results

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T. Topaloglu
Head, Automotive Energy Section
Automotive Technology and Systems Office

D. Elliott
Research Officer
Automotive Technology and Systems Office

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PERFORMANCE OF FIRST GENERATION NGV KITS -- ENGINE AND CHASSIS DYNAMOMETER TEST RESULTS

Toros Topaloglu, Ph.D.
Section Head

David Elliott, Ph.D.
Research Officer
Ontario Ministry of Transportation and Communications
Downsview, Ontario, Canada M3M 1J8

ABSTRACT

The performance of commercial automotive CNG conversion equipment was evaluated by means of engine and chassis dynamometer tests.

In the engine dynamometer tests, four typical conversion systems were assessed on 4.9 L I-6 and 6.1 L V-8 spark-ignition engines. Fuel consumption, power output, exhaust gas composition and temperature were measured under steady-state conditions over the load and speed ranges of the engines both on gasoline (baseline tests) and on natural gas. With one of the conversion systems, the dependence of peak power and part-load efficiency on carburetion (A/F ratio), ignition (spark timing, etc.), exhaust emissions control and engine cooling system parameters was measured and optimized. This work indicates that, as a result of conversion to natural gas, maximum power and specific energy consumption decline under some conditions. Unfortunately, optimization of only spark timing and A/F ratio may not be sufficient to alleviate this problem.

In the chassis dynamometer tests, two of the conversion systems were assessed on a pickup truck equipped with the 4.9 L engine. Fuel consumption and exhaust emissions were measured on gasoline, before and after conversion, and on natural gas over the urban and highway driving cycles strictly according to the Transport Canada Guidelines (and US EPA regulations). The chassis dynamometer results indicate that conversion is accompanied by only a modest increase in average energy consumption, a significant deterioration in acceleration performance, and some improvement in exhaust emission levels. In this paper, these and related results are discussed to explore the potential of improving upon the present CNG conversion technology.

PERFORMANCE OF FIRST GENERATION NGV KITS -- ENGINE AND CHASSIS DYNAMOMETER TEST RESULTS

INTRODUCTION

During 1981 to 1986, the Ontario Government sponsored a number of natural gas vehicle fleet demonstrations. These demonstrations provided, in addition to publicity, hands-on experience with many aspects of compressed natural gas (CNG) utilization and led to the conclusion that the introduction of natural gas to the transportation sector would strongly benefit from technical improvements in on-board vehicle conversion equipment, such as carburetion, ignition and fuel storage components, and improvements in their application. Therefore, the Ministry of Transportation and Communications (MTC) and the Ministry of Energy supported and conducted a number of research and development projects in these areas. This paper is based on the results of the engine dynamometer tests conducted at the University of Toronto and the chassis dynamometer tests conducted at MTC to assess representative commercial CNG/gasoline dual-fuel carburetion equipment in light- to medium-duty automotive spark-ignition engines. This technical assessment is based on comparisons of power, fuel consumption and exhaust emissions data obtained with gasoline and natural gas.

The literature dealing with the use of gaseous fuels in internal combustion engines is not extensive. The performance of gaseous fuels has been assessed in a few single-cylinder engine studies [1 to 5]. Some of this work serves to define the ignition, knock and auto-ignition limits of fuel-air mixtures as a function of major engine operating parameters, such as compression ratio and air-fuel mixture equivalence ratio. More recently, the results of these studies were discussed and augmented by Karim and Wierzba [6], who presented power output, average combustion duration and optimum spark-timing data for methane, propane and methane/propane mixtures.

Evaluation of complete fuel systems rather than the fuel alone were published in the early 1970s by Genslak [7] and Fleming and Allsup [8]. These studies were carried out primarily to assess the potentials of natural gas and propane as means of reducing exhaust emissions of hydrocarbons and carbon monoxide. In both studies, commercial carburetion systems, engines and vehicles of the day were used to determine the effect of engine parameters on exhaust emissions, performance and fuel consumption.

Studies of greater relevance to today's needs have been conducted in parallel with the present work at the British Columbia Research Council [9 to 12], the University of British Columbia [13], and the Southwest Research Institute [14]. In many respects, these efforts are complementary and essential to produce a sufficient data base to adequately

characterize and assess the engine and conversion system combinations in the marketplace and in R&D laboratories. This paper does not attempt to compile and unify the information in the above references; however, it does make selective use of them to explain and generalize the results reported here.

ENGINE DYNAMOMETER STUDY

Test Program

In the engine dynamometer study [15,16], first-generation carburetion systems were tested on two light- to medium-duty production gasoline engines -- Ford 4.9 L I-6 and 6.1 L V-8 engines. The first generation systems are based on conventional diaphragm regulators and some type of vacuum operated mixer. These constitute practically all systems in use and are still being sold. The commercial mixers may be categorized into three groups: flow nozzle, air valve and venturi types. The NGV conversion industry commonly employs flow nozzle mixers, since they are more readily applicable to dual-fuel rather than mono-fuel operation. The propane conversion industry, on the other hand, prefers the air valve and venturi mixers, which seem to be more suited to mono-fuel applications.

In the first phase of the program, all three types of mixers were tested on the 4.9 L I-6 engine. The flow nozzle type was represented by the Diversified Fuel Components (DFC) and CNG Fuel Systems (CFS) mixers, the air valve type by the IMPCO mixer and the venturi type by the BEAM mixer. The DFC and CFS systems are completely equipped for installation on CNG vehicles while the IMPCO and BEAM systems, with only two-stage regulators, necessitated the use of a high-pressure preregulator. In the second phase of the program, only the flow nozzle mixers supplied by DFC, CNG and Garretson were evaluated on the 6.1 L V-8 engine.

Both engines were first tested on gasoline (baseline testing). Then, they were converted to natural gas operation with each conversion system, either directly by the equipment supplier or according to the suppliers instructions, and extensively tested to determine performance, fuel consumption and exhaust emissions. In these tests, all engine calibration parameters except those dictated by the gas carburetion systems and the dual-curve ignition control unit were kept at the engine manufacturer's specification.

Subsequent to the completion of all tests with every conversion system, optimization experiments were performed with both engines and a selected conversion system. During this process, wide open throttle (WOT) power output and part-load efficiency were maximized by varying mixture strength (air-fuel ratio) and ignition timing, the two

engine calibration parameters with the greatest influence on performance, fuel consumption and exhaust emissions.

The engine dynamometer tests were performed in the Engine Research and Development Laboratory of the University of Toronto on a GO-POWER (Model 557 B) hydraulic dynamometer and a University of Toronto make AC variable frequency electric dynamometer according to the SAE Standard J816 B and the GM Engine Test Code, VI Edition, Test 1. The measurements included torque, gasoline and natural gas consumption, and hydrocarbon (HC), nitrogen oxides (NO_x), oxygen (O_2), carbon monoxide (CO) and carbon dioxide (CO_2) concentrations in the exhaust under a set of steady-state conditions, i.e., at specific engine load and speed points. Both gasoline and natural gas consumption were measured gravimetrically with a ± 2% accuracy. In addition to these primary parameters, engine speed, inlet air and manifold air-charge temperatures, average and individual port exhaust temperatures, spark timing, manifold pressure, lubrication oil pressure, relative throttle position, barometric pressure, ambient temperature and humidity were monitored.

Discussion of Results

Power. Engine performance was assessed by the WOT maximum power measurements over the speed range of 1200-3600 rpm. These results along with the corresponding torque data are presented in Figures 1 and 2 for the 4.9 L and 6.1 L engines respectively. In both figures, it is evident that at all speeds a significant power loss is suffered by the engines due to the conversions. Specifically, the magnitude of this loss is 12 to 22% for the 4.9 L engine and 6 to 15% for the 6.1 L engine, depending on the conversion system and engine speed considered. The more unfavourable results with the Garretson unit are not included in these ranges, since they are not representative. However, it is worth noting that improper equipment selection, as experienced in the Garretson unit case, may impose a performance penalty of as high as 36%.

The theoretically expected WOT power drop with natural gas can be predicted by comparing representative values of the charge energy density of gasoline, viz. 84.6 MJ/kmol, with that of natural gas, viz. 75.5 MJ/kmol, under stoichiometric combustion conditions. By this comparison, a WOT power drop of 10.8% is expected. However, the conversion process is accompanied by changes in addition to the combustion thermochemistry, e.g., volumetric efficiency, air-fuel ratio and ignition timing changes. Therefore, the theoretical figure of 10.8% serves merely as a reference point.

Fuel Consumption. The basis for the fuel consumption comparisons in this section is the brake specific fuel consumption (BSFC), which represents the gravimetric fuel consumption of an engine per unit of brake power output at any operating condition other than at idle. The use of this

figure of merit allows more direct comparisons to be made between engines of different displacements.

The BSFC data for the six-cylinder engine are presented in Figures 3 and 4 and those for the eight-cylinder engine in Figures 5 and 6. It is clear that these data represent more than one significant trend. With the smaller engine, natural gas consumption is larger than gasoline consumption at higher engine loads and speeds with most of the conversion systems. However, at least with one of the conversion systems (DFC system), natural gas consumption is consistently lower than gasoline consumption except at the top end of the engine speed range.

With the larger engine, which is evidently less efficient than the smaller one, conversion to natural gas appears to have resulted almost always in lower fuel consumption. The only exception is the Garretson unit, which as noted previously, represents an inappropriate equipment selection. It is also worth noting that while the CFS mixer used with the 4.9 L engine performed poorly, the larger unit used with the 6.1 L engine did reasonably well. This indicates that mixer sizing rather than mixer type may provide a better explanation for the performance of the CFS units.

The differences in BSFC from one conversion system to another is best correlated by the equivalence ratio of the air-fuel mixture, which was determined from exhaust gas measurements at each operating point. Figure 7 is an example of this correlation for the 6.1 L engine running at 33% load and 2400 rpm. Here the BSFC is expressed on an energy rather than mass basis in order to have a direct comparison of efficiencies. As seen in this figure, BSFC decreases or energy efficiency increases with increasing equivalence ratio. The only contradiction to this rule is the CFS mixer which despite providing a leaner mixture than the DFC unit results in less efficient operation. This discrepency was observed at a number of operating points and may be explained by considering volumetric efficiencies.

Ignition timing is another calibration parameter which may influence fuel consumption. However, the use of the same ignition control unit in all conversions resulted in similar total ignition delay curves and thus did not constitute significantly to differences in fuel consumption.

Exhaust Emissions. In this section, the emissions of HC, CO and NO_x are assessed on the basis of their concentrations in exhaust gases under steady-state conditions. These are relative results only and cannot be directly compared with legislated standards. They are derived from measurements on raw exhaust gases, viz., exhaust gases sampled before any exhaust treatment device. This practice arose from the need to determine air/fuel ratios from exhaust gas compositions and to obtain comparable results from the test engines which are not equipped with the same emission control equipment (Table 2). Due to these

limitations, a quantitative discussion of the emissions is reserved for the chassis dynamometer data. Here, the trends observed with HC, CO and NO_x emissions with the two engines and two fuels are summarized.

The HC emission levels are, in general, higher with natural gas than with gasoline; however, most of this HC is expected to be methane as demonstrated in [17]. The exception to this trend was observed with the 6.1 L engine at lower engine speeds, where the larger engine exhibits poor vapourization and mixing with gasoline. This may suggest the desirability of natural gas in such cases.

The CO emission levels are generally lower with natural gas than with gasoline. The largest benefit with natural gas in CO emissions was observed at high loads, where conventional gasoline carburetion systems are calibrated rather rich.

The NO_x emission levels are generally higher with natural gas than with gasoline. This trend applied better to the 6.1 L engine, which is clearly less efficient than the 4.9 L engine. The higher NO_x emissions are indicative of higher peak combustion temperatures and thermal efficiencies.

Further explanations for the emissions, fuel consumption and performance trends may be found in the air-fuel ratio trends presented for the 4.9 L engine in Figure 8. Here, we observe that the gasoline carburetor is capable of producing a relatively lean mixture at part-load operation and sufficient enrichment at idle and full-load to ensure good idling and acceleration performance. The natural gas mixers, on the other hand, appear to be incapable of generating such an air-fuel ratio schedule. In general, they produce leaner idle mixtures and richer part-load mixtures, which are conducive to higher HC emissions and lower fuel efficiencies.

Potential for Optimization

The potential for full-load torque and part-load efficiency gains by optimal ignition timing and air-fuel ratio (A/F) adjustment was assessed with both engines and one of the conversion kits. The full-load optimization produced the leanest for best torque (LBT) air-fuel ratio and the minimum for best torque (MBT) advance as well as the maximum torque attained at three engine speeds. In the iterative process leading to these results, ignition timing and air-fuel ratio were adjusted manually by adjusting the distributor and the reference pressure in the third stage of the regulator. The part-load optimization produced the optimum timing and air-fuel ratio along with the corresponding BSFC at 1/3 and 2/3 of MBT torque and at three engine speeds.

The results of this optimization exercise were rather disappointing. The maximum torque produced with the calibration settings recommended by suppliers could not be improved upon. Part-load fuel consumption, on the other hand, was reduced by 0 to 8% in the 4.9 L engine and 1 to 9% in the 6.1 L engine. The major gains were attained at 2/3 load and higher speed conditions, as documented in Table 3.

CHASSIS DYNAMOMETER STUDY

Test Program

In the chassis dynamometer program, which was conducted in the MTC laboratory, the DFC and CFS conversion systems of Table 1 were evaluated on a Ford F-150 pick-up truck equipped with the Ford 4.9 L I-6 engine.

The CFS conversion kit was installed and calibrated by the supplier while the DFC kit by MTC staff according to the supplier's instructions. With both kits the vehicle was operated as an NGV/gasoline dual-fuel vehicle and was equipped with the Autotronic dual-curve ignition control module.

The vehicle was tested on gasoline before and after its conversion. The results of these two test series helped to establish the vehicle baseline performance and the effects of the two conversions in the gasoline mode. This was followed by extensive tests on natural gas with both conversion systems. In each of these test series, fuel consumption and exhaust emissions were measured over the EPA urban and highway driving cycles presented in Figure 9. Supplementary tests were performed to measure fuel consumption under steady-state conditions, acceleration performance, spark-timing schedule and air-fuel ratio schedule.

In addition, the utility of the dual-curve ignition device and the implementation of disabling some of the emission control devices, i.e., the exhaust gas recirculation (EGR) and air pump (AP) systems, were assessed in separate tests. Details of this test program can be found in Reference [18], an MTC report.

Discussion of Results

Performance. The acceleration performance of the test vehicle was assessed by measuring the minimum time required to reach 96.6 km/h from stand-still. This entailed full-throttle acceleration in drive and second gears. The average test results are provided in Table 4 for the gasoline and natural gas modes. These indicate that the conversion process may produce a small change in acceleration performance on gasoline. With the DFC kit, this change is 9 to 10% increase in performance, whereas with the CFS kit,

there is a 13 to 19% decrease. The conversion kits inevitably add more restriction to air flow in the induction system of the engine, which, with everything else remaining unchanged, would produce a decline in performance. However, since the conversion systems affect fuel flow and ignition timing as well, the overall effect of a specific system, such as the DFC, may be an improvement in performance.

The switch to natural gas is expected to result in a noticeable decline in acceleration performance. Indeed, comparison of the test results in Table 4 indicates that the dual-fuel vehicle operating on natural gas tanks, on the average, 15 to 20% longer to accelerate from 0 to 96.6 km/h than the baseline gasoline vehicle. The two conversion systems have a similar impact on acceleration performance. The loss of power observed with natural gas is largely due to its gaseous state. On the basis of a smaller charge energy density, a 10 to 11% drop in WOT power and acceleration performance is expected. The greater loss in performance observed in this study may be partially due to additional volumetric efficiency losses caused by the NG carburetion equipment and the smaller flame speed in natural gas-air mixtures. The NG carburetion system adds to flow restrictions and increases the charge temperature, resulting in lower volumetric efficiency and acceleration performance.

Fuel Consumption. The assessment of natural gas as a transportation fuel has to involve a comparison of its combustion efficiency with that of gasoline. To this end, series of fuel economy tests were carried out with gasoline before and after vehicle conversion. The results of the first test series indicate that the average fuel consumption of the baseline gasoline vehicle is 14.63 L/100 km on the urban and 12.10 L/100 km on the highway driving cycles. The combined fuel consumption figure representing 55% urban and 45% highway driving is 13.49 L/100 km which is only 3 to 4% higher than the 13.0 L/100 km figure provided in the Transport Canada fuel consumption guides. The data obtained in the second test series with the dual-fuel gasoline vehicle indicate that the two kits have very similar effects on fuel consumption. Therefore, it is appropriate to compare the average values of these results with the baseline data, as is done in Table 5 and Figure 10. This comparison reveals that the kits increase vehicle fuel consumption by approximately 8% under urban driving conditions. However, they do not affect highway fuel consumption. The idle and 48.3 km/h cruise test data show fuel consumption increases of 25.4% and 4.6%, respectively. The main contribution to the urban fuel economy decline appears to take place under cold-start and warm-up conditions, as indicated by the 17.1% increase in the cold-transient phase fuel consumption readings in Table 5. This would suggest that in city driving, especially when small trips and excessive idling is involved, the use of gasoline in the dual-fuel vehicle would entail significant fuel losses.

The natural gas consumption of the F-150 pick-up truck was measured with two versions of the DFC kit and the CFS kit. As seen in Table 6, the three kits resulted in very similar natural gas consumption figures. Specifically, in all driving modes, except at 96.6 km/h cruise, the difference in fuel consumption in $m^3/100$ km is within 2 to 3%.

It is difficult to compare directly the efficiency of natural gas combustion with gasoline combustion by simply looking at fuel consumption results, because the two fuels have different energy densities. Thus, it is preferable to compare energy consumption figures which were derived from the fuel consumption data by using the lower heating values of gasoline, 32.4% MJ/L, and of natural gas, 33.6 MJ/m^3. The results are summarized in Figure 10. This analysis reveals that the average energy consumption of the converted vehicle in the natural gas mode is approximately 2.5% higher than that of the baseline gasoline vehicle in both urban and highway driving. Under cruise conditions, 3.5 to 4.5% more energy appears to be consumed with natural gas. However, at idle, this trend is reversed and 10 to 11% less energy is consumed with natural gas.

Figure 11 includes the energy consumption of the converted vehicle on gasoline which allows comparison of the efficiencies of the dual-fuel vehicle on natural gas and gasoline. This comparison indicates that, on the average, the converted vehicle is more efficient on natural gas than on gasoline. This advantage is 4.7% in urban driving, 2.2% in highway driving, and as much as 30% at idle. Thus, the conversion of the vehicle results in a decrease of its energy efficiency. However, this decrease is very small in the natural gas mode.

Exhaust Emissions. The exhaust emissions of HC, CO and NO_x were measured strictly according to the Canadian and US Federal Governments' test procedures specified in References [19] and [20]. The urban and highway test cycles prescribed in these test procedures are illustrated in Figure 9. The Canadian and US exhaust emission standards relate to only the urban cycle, which is commonly referred to as the CVS-CH cycle.

The levels of HC, CO and NO_x emissions are quantified in terms of the mass of each pollutant emitted per unit distance. The units selected for this quantity are those specified in the standards, viz., g/mile. The emission levels of the baseline and dual-fuel vehicle were measured on gasoline and on natural gas with each conversion system. The averages of the results are provided for comparison in Figures 12 to 14 for HC, CO and NO_x, respectively.

Over the urban cycle, the baseline vehicle produced 0.54 g/mi HC, 3.76 g/mi CO and 1.57 g/mi of NO_x, which are well within the present Canadian light-duty vehicle

exhaust emission standards. In fact, it is apparent that this vehicle is designed to meet the much more stringent US emission standards. The highway HC, CO and NO_x levels were 0.13, 2.24 and 2.81 g/mi, respectively. As expected, under highway driving conditions, less HC and CO but more NO_x are emitted than under urban driving conditions.

Figures 12 to 14 reveal that vehicle conversion has significant effects on all three pollutant levels. HC emissions, which result mainly from unburnt fuel, are adversely affected by the conversions both in the gasoline and natural gas modes. The increase is more pronounced in the urban cycle and results in 2.83 g/mi HC on natural gas, which exceeds the 2.0 g/mi Canadian standard. However, with natural gas, most of the unburnt fuel is methane [17], which has a very low reactivity and toxicity.

The effect of the conversions on CO emission levels was found to depend strongly on the specific conversion system considered. The average effect under urban driving conditions is one of improvement with natural gas and deterioration with gasoline. The effect of the conversions on NO_x levels was less pronounced. In the gasoline mode and on the urban driving cycle, the DFC system caused a slight increase in NO_x emission, whereas the CFS system caused a decrease. Exactly the opposite occurred in the natural gas mode, viz, the DFC system caused an increase and the CFS one a decrease in NO_x emissions. In summary, the dual-fuel vehicle in its gasoline mode produced more HC and CO and less No_x. In its natural gas mode, it produced more HC and less CO and NO_x.

In an effort to explain some of the above observations, the air-fuel mixture equivalence ratio was measured as a function of vehicle speed. The results for the baseline gasoline, dual-fuel gasoline and natural gas modes are presented in Figures 15 to 17. The data in Figure 16 indicate that the baseline vehicle is calibrated to run approximately 10% rich at idle and slightly lean over the 40 to 100 km/h range. In the 0 to 30 km/h range the equivalence ratio could not be reliably determined because of large fluctuations during each measurement.

Figure 16 suggests that the conversion systems affect the performance of the gasoline carburetor. The notable effect is an enrichment of the air-fuel mixture at the higher speeds, which may be due to the flow restriction introduced by the natural gas mixers. Figure 17 shows that the DFC and CFS conversions, as adjusted by the suppliers, produce distinctly different air-fuel mixture compositions with natural gas. Specifically, the DFC system produces a stoichiometric to slightly lean mixture over the entire vehicle speed range, whereas the CFS system always produces a rich mixture except at idle.

The trends noted above explain some of the experimental observations. The richer air-fuel mixture in the dual-fuel gasoline mode is responsible for the higher CO emissions with both the DFC and, especially, the CFS systems. It also contributes to the higher HC emission levels and the lower NO_x levels, especially with the CFS system. The effects of the A/F ratio on emissions in the natural gas mode are more difficult to explain, since this case includes more changes with respect to the baseline case. The very low CO emission levels with the DFC system are consistent with the leaner carburetion. Similarly, the higher CO emission levels with the CFS system may be explained by the stoichiometric A/F ratio at idle and the relatively rich A/F ratios at higher vehicle speeds. However, the higher NO_x emission levels with the CFS system are not consistent with the richer carburetion.

Removal of Exhaust Emission Control Measures

In an effort to simulate possible tampering with exhaust emission control devices, the exhaust gas recirculation (EGR) and air pump (AP) systems of the test vehicle were disabled individually. Both of these actions did not produce any significant fuel consumption and acceleration benefits. However, they resulted in unacceptably high levels of NO_x and CO pollution with natural gas. Specifically, with EGR removed NO_x emissions increased to 9.79 g/mi and with AP removed CO missions reached 15.90 g/mi over the urban cycle.

Effects of the Dual-Curve Ignition Device

The use of the dual-curve ignition control device (ICD) was compared with the common strategy of advancing static timing by 10°. The static advance has a major effect on maximum engine power, fuel consumption, combustion characteristics (detonation and preignition), and exhaust emissions levels. Its selection depends on the fuel and, to a lesser extent, engine characteristics. The choice made in natural gas conversions is aimed at providing adequate power and fuel economy in the natural gas mode while avoiding engine knock in the gasoline mode.

The timing schedules or timing curves (with and without vacuum advance) of the test vehicle in its baseline gasoline configuration are presented in Figure 18 and those in the gasoline and natural gas modes in Figures 19 and 20, respectively. Comparison of Figures 18 and 19 indicates that, in the gasoline mode, the dual-curve ICD is basically duplicating the ignition timing curve of the baseline configuration. The maximum deviation between the two timing curves is only 2°, with the dual-curve ignition system output being

more advanced. Advancing the static or base timing by 10° results in almost a constant 10° advance throughout the engine speed range, as indicated by the data in Figure 20. Thus, without the ignition device, the spark timing of the dual-fuel vehicle in its gasoline mode is always 10° advanced with respect to the original equipment manufacturer's design.

In the natural gas mode, substantially different timing schedules are observed, with and without the dual-curve ICD (Figure 21). Specifically, total timing (centrifugal and vacuum advance) with the ignition control device is 10° to 20° more advanced than without it.

The effects of the dual-curve ICD on fuel consumption, exhaust emissions and acceleration performance were measured in the natural gas and gasoline modes. In the natural gas mode, the ignition control device produces substantial acceleration performance and pollution control benefits; however, it results in a 3.2% fuel consumption increase. In the gasoline mode, the dual-curve ICD does not provide any benefits.

CONCLUSIONS

In this paper, engine and chassis dynamometer data are presented to assess the performance, fuel consumption and exhaust emission effects of common NGV conversion systems in two spark-ignition engines and a light-duty vehicle. The engine dynamometer data were obtained under steady-state conditions while most of the chassis dynamometer data were generated over driving cycles representative of urban and highway trips.

With the specific equipment tested, conversion to natural gas was found to degrade acceleration performance by 15 to 20%, which may be limited to approximately 10% by minimizing volumetric efficiency losses and enhancing power enrichment. Energy consumption increased under most steady-state operating conditions (cruising) and decreased at idle and under transient operating conditions (acceleration and deceleration). The net result of these opposite trends was a 2 to 3% difference between natural gas and gasoline combustion efficiencies over the EPA urban and highway driving cycles. The exhaust emission levels of CO and NO_x were generally lower with natural gas than with gasoline. However, this environmental advantage exists only when all gasoline emission control equipment are left operational.

Dual-fuel vehicles operated on gasoline were found to have significant power, fuel consumption and exhaust emission disadvantages relative to the baseline vehicle. Thus, there is a further reason to minimize operation of these vehicles on gasoline.

Engine dynamometer experiments with the first generation conversions indicate that the potential for performance and efficiency improvements by optimal adjustment of spark timing and air-fuel ratio are small.

Major progress in the utilization of natural gas as a spark-ignition engine fuel has to await engine design changes to allow for the combustion characteristics of natural gas.

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Table 1/ Specifications of NGV Carburetion Systems Tested

Carburetion System		Ford I-6	Ford V-8
DFC			
Regulator	Stages	3	
	Model	Tartarini RP/76	Tartarini RP/76
Mixer	Type	flow nozzle	flow nozzle
	Model	CNG	UM-2
CFS			
Regulator	Stages	3	3
	Model	Landi Renzo GM78 size TN-2C	Landi Renzo GM78 size TN-2S
Mixer	Type	flow nozzle	flow nozzle
	Model	CNG	CNG
IMPCO			
Regulator	Stages	2 *	
	Model	EBS with ECI	
Mixer	Type	air valve	
	Model	CA-225 NG air valve DA-1793-RS	
BEAM			
Regulator	Stages	2 *	
	Model	450 B	
Mixer	Type	Venturi	
	Model	C5-60-H6 NG venturi 310A-N48	
GARRETSON			
Regulator	Stages		3
	Model		Tartarini RP/76
Mixer	Type		flow nozzle
	Model		

* In these cases, a high pressure (3000/200 psi) preregulator (Matheson Model 1H) was used.

Table 2/ Engine Specifications

Characteristic	Engine	
	Ford I-6	Ford V-8
Displacement,L	4.9	6.1
Compression ratio	8.6:1	8.0:1
Bore, mm	101.6	101.6
Stroke, mm	101.09	93.48
Carburetor	Carter 1 barrel	Holley 4 Barrel
Distributor	Motorcraft Duraspark II	Motorcraft Duraspark II
Emission controls *	EGR PCV EEC TAC CC AP	EGR PCV AP

* Emission Control Devices:
EGR - Exhaust gas recirculation
PCV - Positive crankcase ventilation
EEC - Evaporative emission control
TAC - Thermostatic air cleaner
CC - Catalytic converter
AP - Air pump

Table 3/ Part-Load (2/3 Load) Optimization Results

Ford 4.6 L I-6 Engine				
1. Engine speed	(rpm)	1600	2500	3500
2. BSFC Commercial calibration	(g/kWh)	260	279	379
3. BSFC Optimal calibration	(g/kWh)	260	271	350
4. Change in BSFC	(%)	0	-2.9	-7.7
5. Optimum timing	(deg BTDC)	29	34	34
6. Optimum A/F		17.0	17.2	19.5
Ford 6.1 L I-6 Engine				
1. Engine speed	(rpm)	1200	2100	3000
2. BSFC Commercial calibration	(g/kWh)	280	293	363
3. BSFC Optimal calibration	(g/kWh)	277	288	332
4. Change in BSFC	(%)	-1.1	-1.7	-8.5
5. Optimum timing	(deg BTDC)	36	41	48
6. Optimum A/F		19.8	18.9	17.9

Table 4/ Acceleration Performance in Gasoline and Natural Gas Modes

Vehicle Mode	Acceleration Time (s)	
	in "Drive"	in "Second"
Gasoline, Baseline	14.9	16.0
Gasoline, DFC System	13.4	14.5
Gasoline, CFS System	16.9	19.0
NGV, DFC System	17.2	17.1
NGV, CFS System	19.4	19.3

Table 5/ Gasoline Consumption of the Test Vehicle (MTC Chassis Dynamometer Test Results)

Fuel Consumption (L/100 km)	Baseline	Dual-Fuel Configuration DFC System	CFS System	Average
Urban Cycle	14.63	15.61	15.84	15.79
Cold-Transient Phase	14.79	17.21	17.42	17.32
Stabilized Phase	14.77	15.36	15.70	15.53
Hot-Transient Phase	14.23	14.83	14.88	14.86
Highway Cycle	12.10	11.97	12.28	12.13
Combined (Urban & Hwy.)	13.49	13.97	14.24	14.14
Steady-State Operation				
Idle "Drive" (L/h)	2.05	2.56	2.57	2.57
Idle "Park" (L/h)	2.07	2.44	2.45	2.45
48.3 km/h	8.69	9.39	8.79	9.09
96.6 km/h	13.46	13.57	13.53	13.55

Table 6/ Natural Gas Consumption of the Test Vehicle (MTC Chassis Dynamometer Test Results)

Fuel Consumption (m^3/100 km)	DFC Kit-1	DFC Kit-2	CFS Kit	Average
Urban Cycle	14.46	14.30	14.62	14.46
Cold-Transient Phase	15.20	15.67	16.20	15.69
Stabilized Phase	14.07	14.12	14.43	14.21
Hot-Transient Phase	14.57	13.61	13.86	14.01
Highway Cycle	11.81	11.90	12.14	11.95
Combined (Urban & Hwy.)	13.72	13.22	13.50	13.33
Steady-State Operation				
Idle, in "Drive" (m^3/h)	1.73	1.81	1.73	1.76
Idle, in "Park" (m^3/h)	1.79	1.88	1.86	1.84
48.3 km/h	8.66	8.88	8.51	8.68
96.6 km/h	14.17	13.41	13.12	13.57

NOTE: DFC Kit-1 and DFC Kit-2 refer to the first and second versions of the Diversified Fuel Components Co. kit.

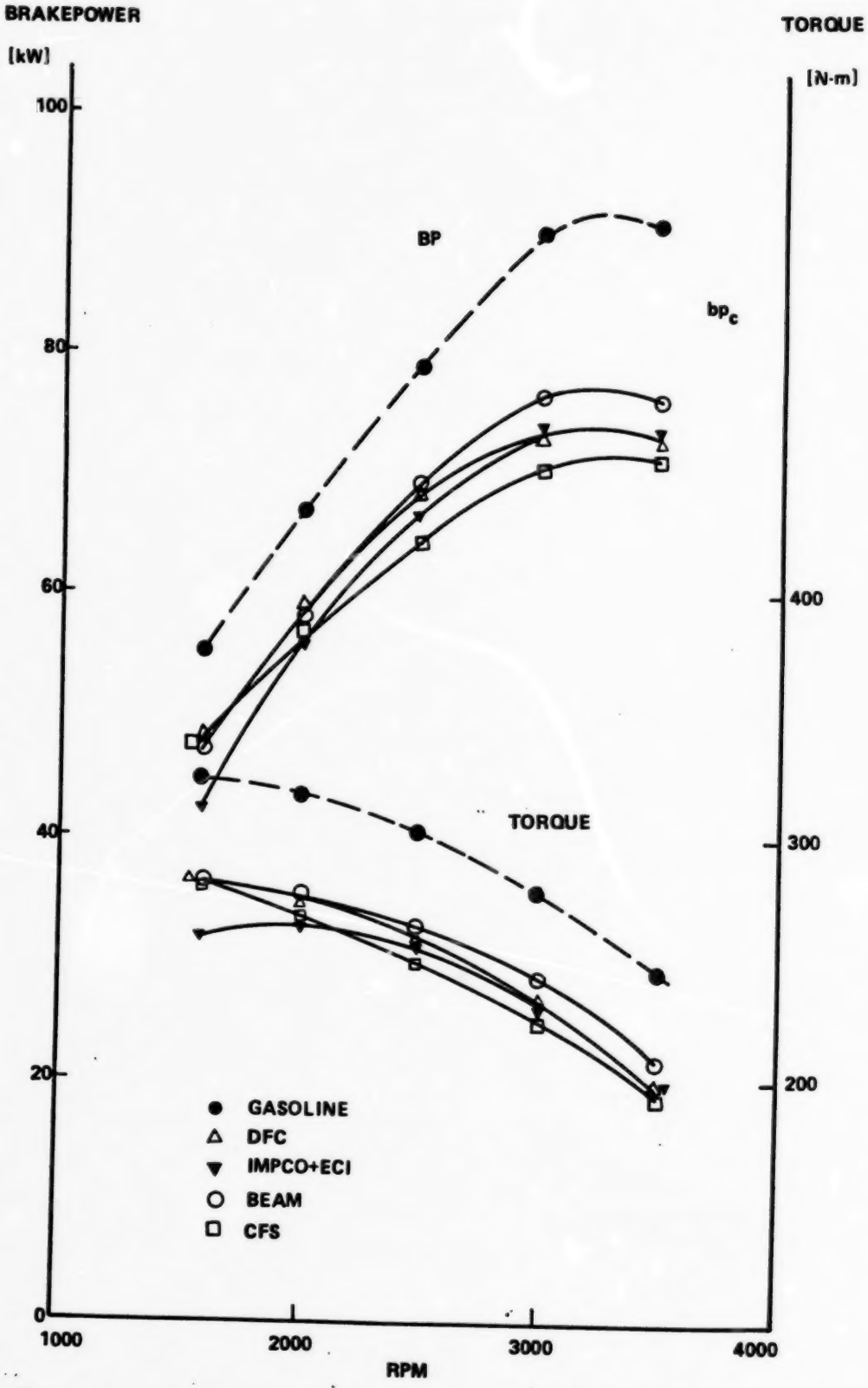


Figure 1/ Comparison of Power and Torque at Wide Open Throttle (4.9 L I-6 Engine)

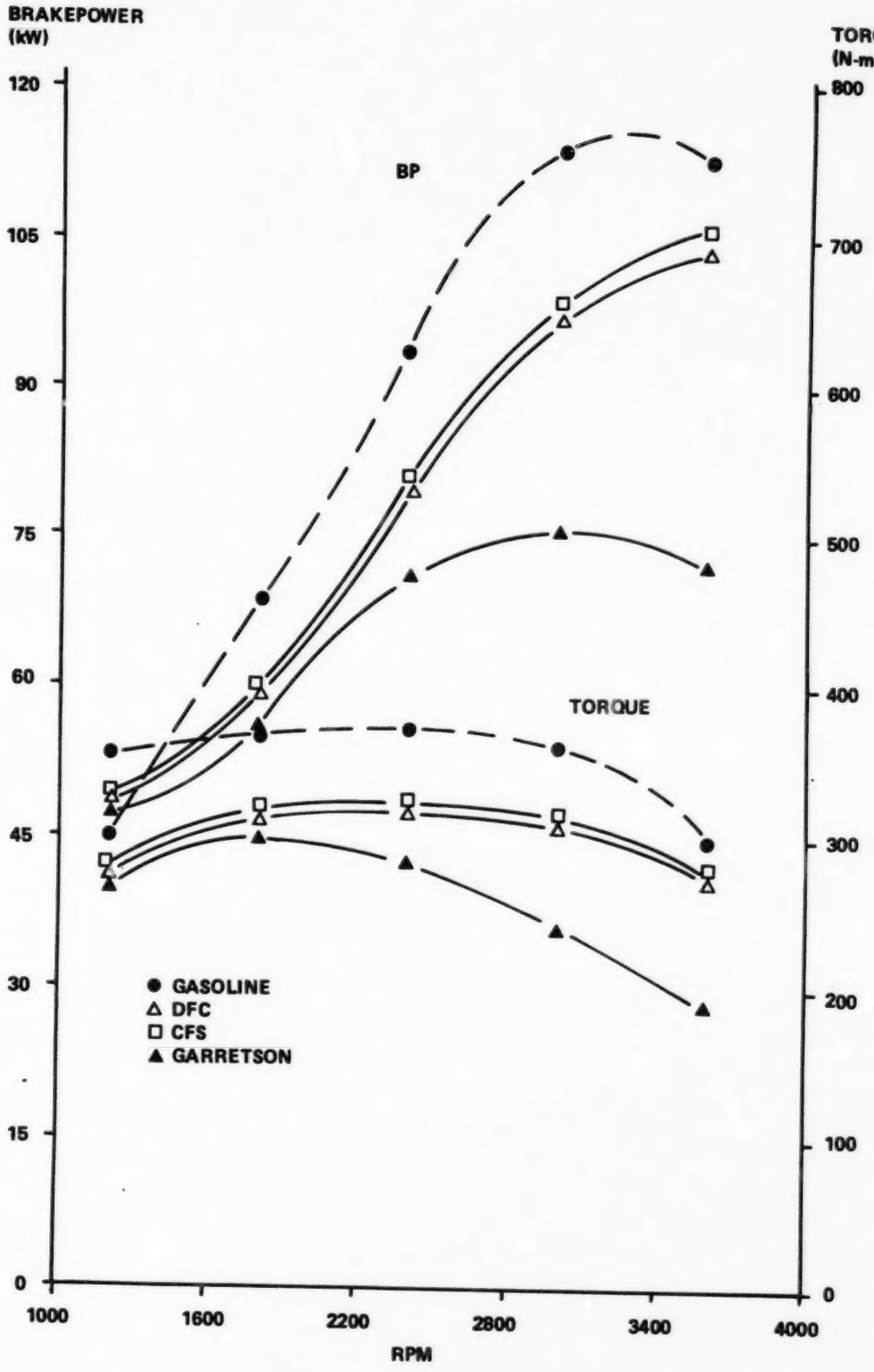


Figure 2/ Comparison of Power and Torque at Wide Open Throttle (6.1 L V-8 Engine)

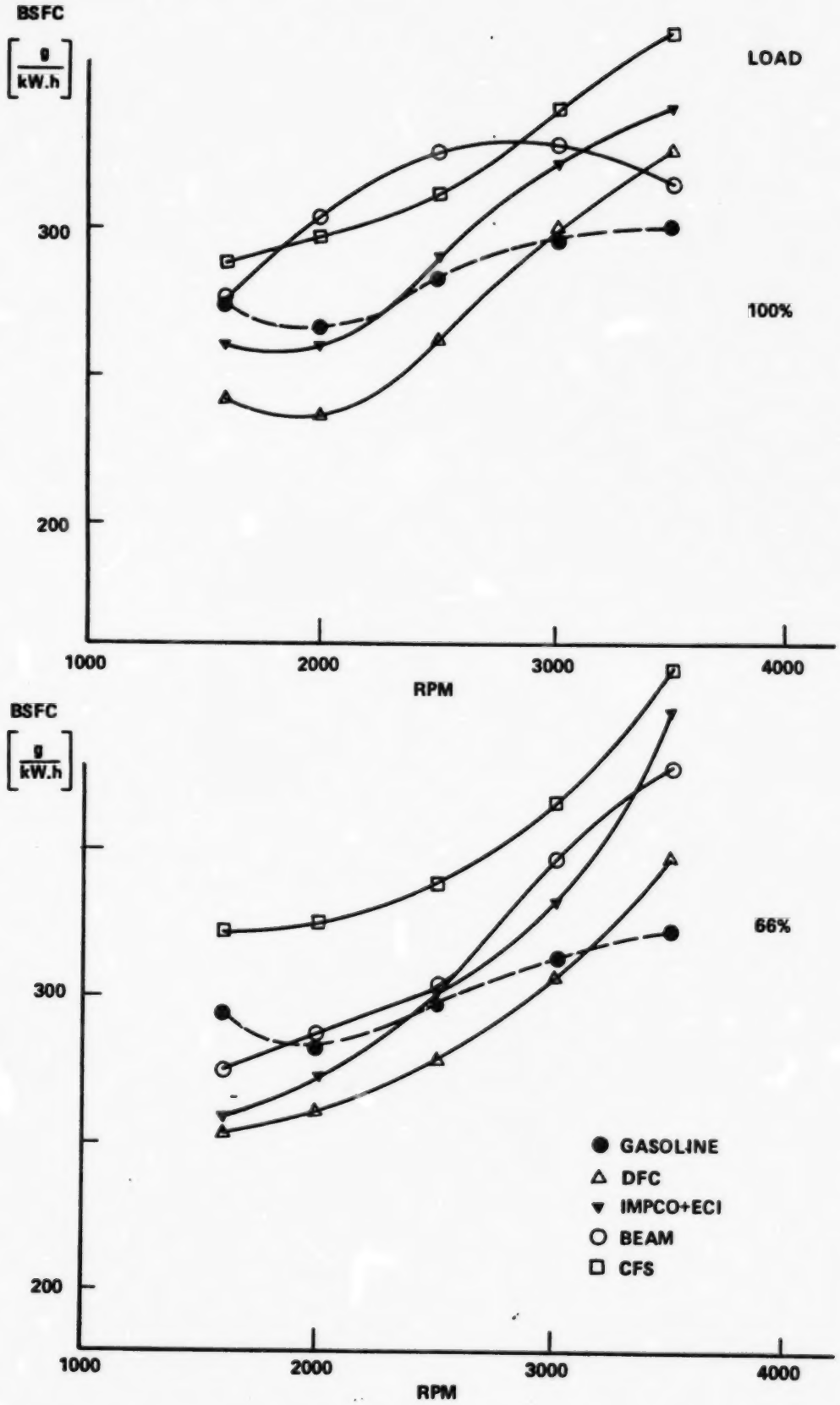


Figure 3/ Comparison of Brake Specific Fuel Consumption at 100% and 66% Load (4.9 L I-6 Engine)

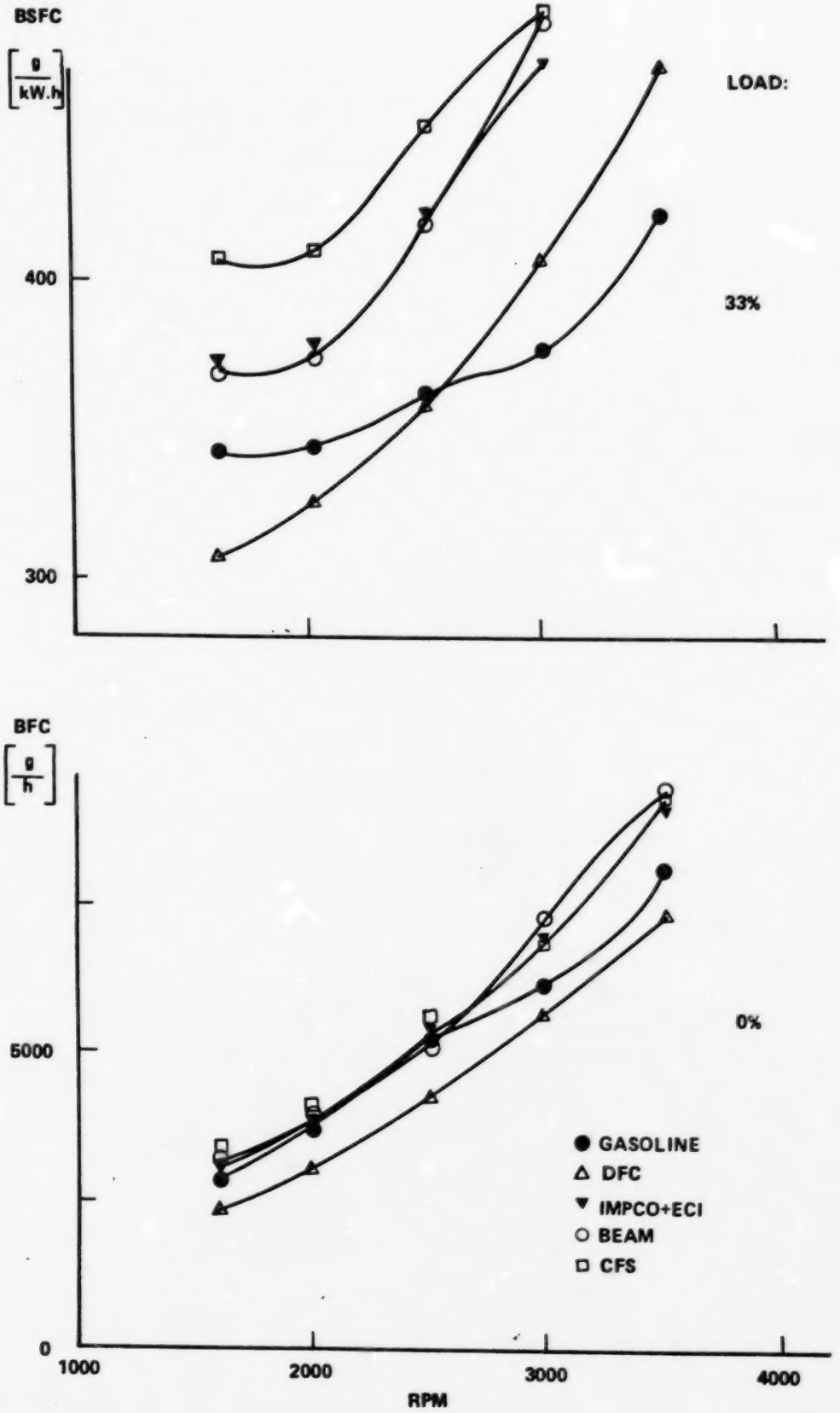


Figure 4/ Comparison of Brake Specific Fuel Consumption at 33% and 0% Load (4.9 L I-6 Engine)

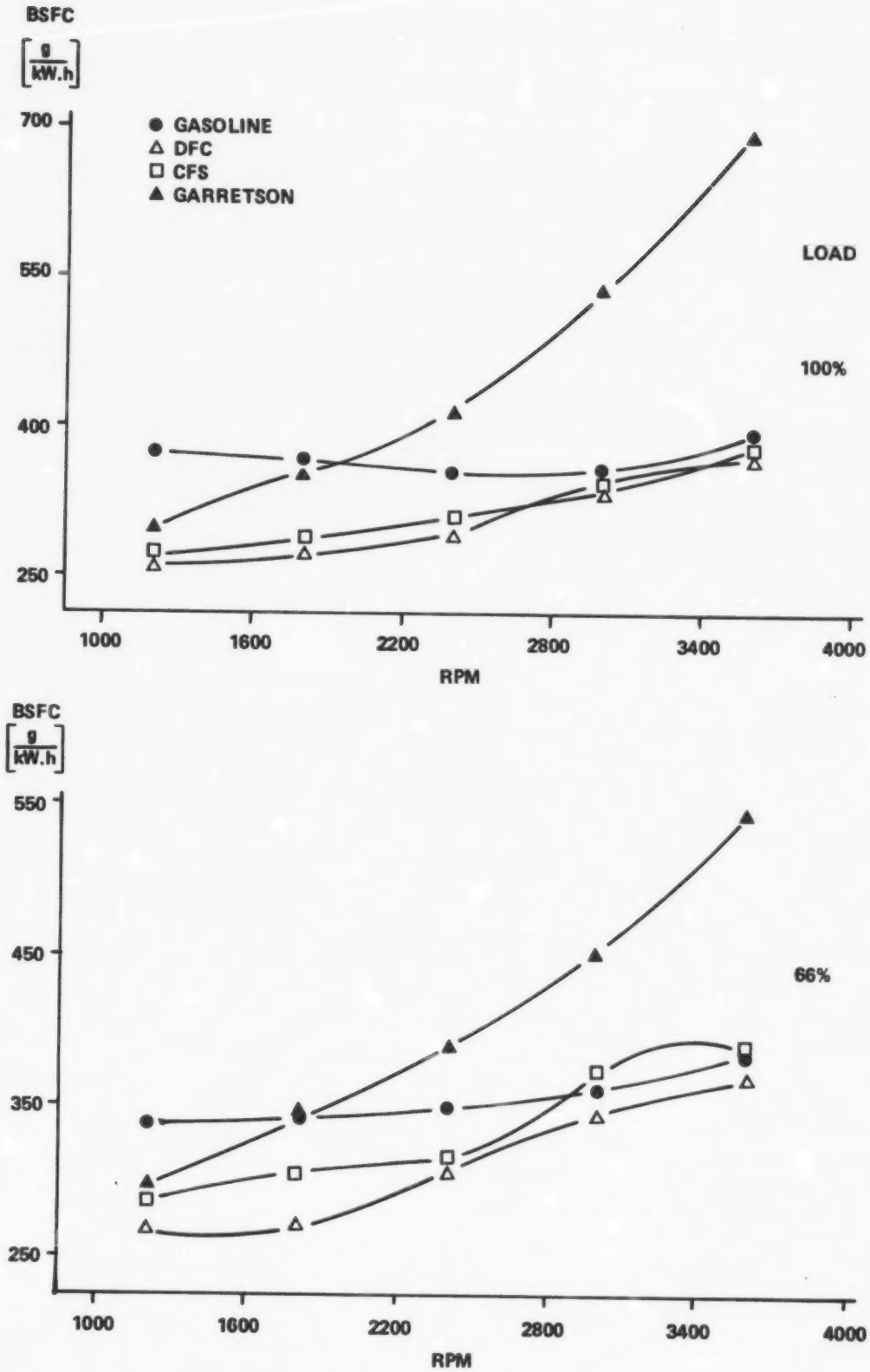
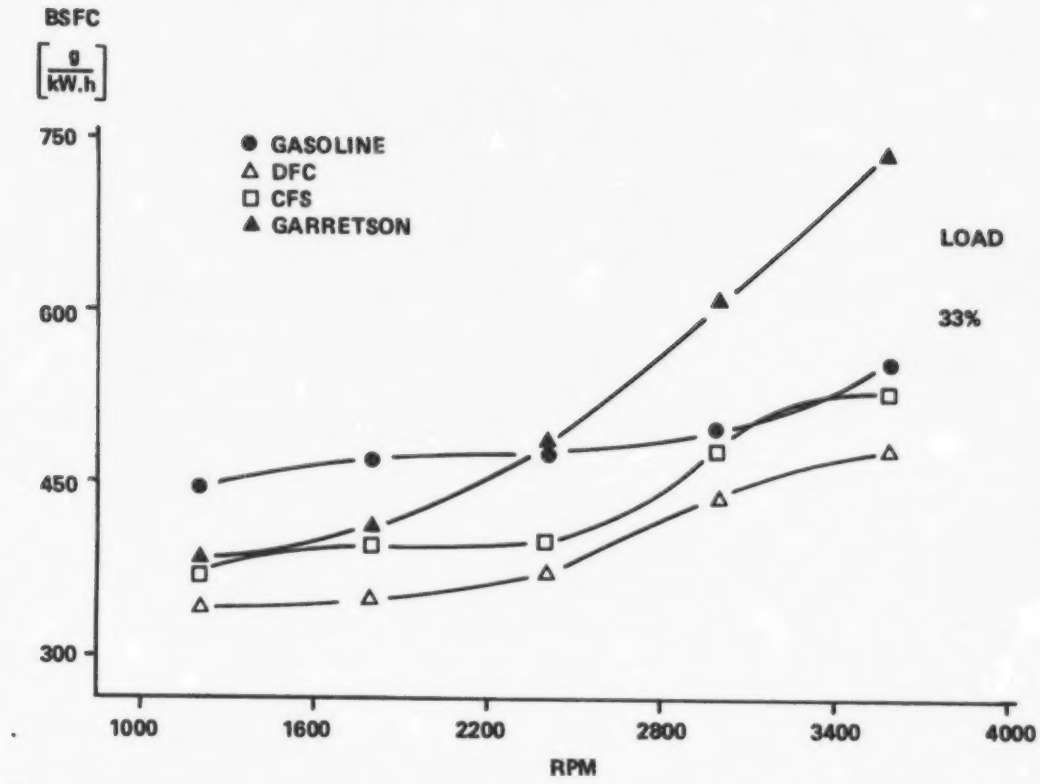


Figure 5/ Comparison of Brake Specific Fuel Consumption at 100% and 66% Load (6.1 L V-8 Engine)



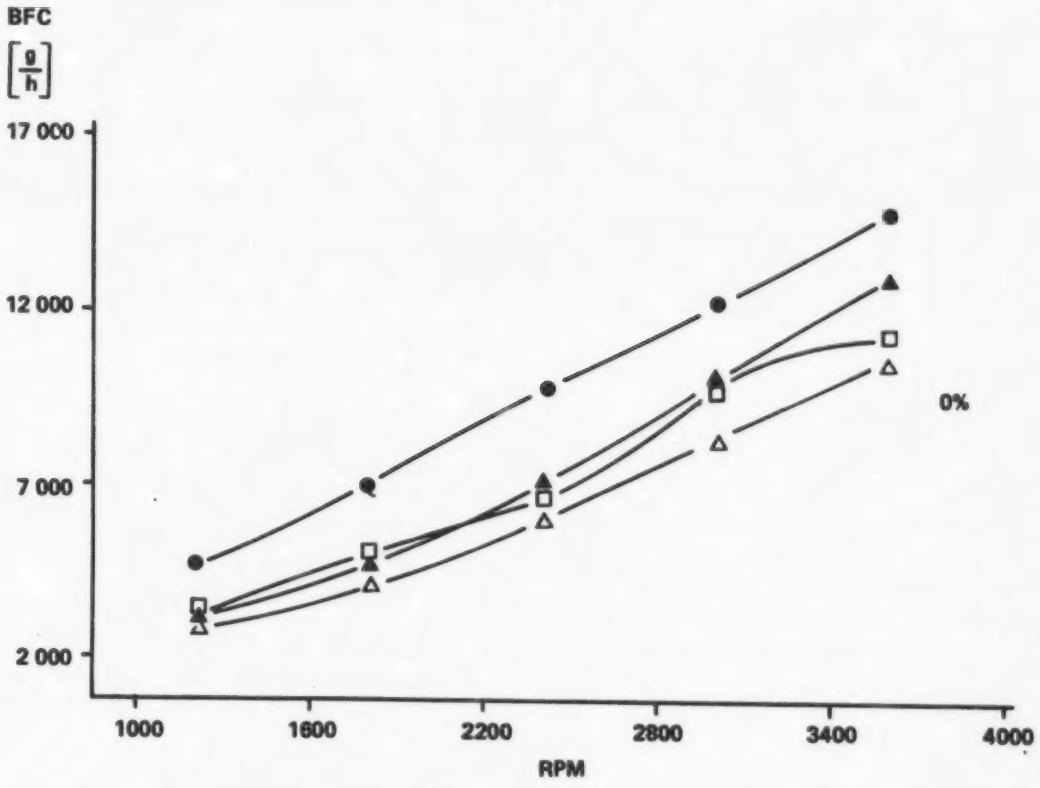


Figure 6/ Comparison of Brake Specific Fuel Consumption at 33% and 0% Load (6.1 L V-8 Engine)

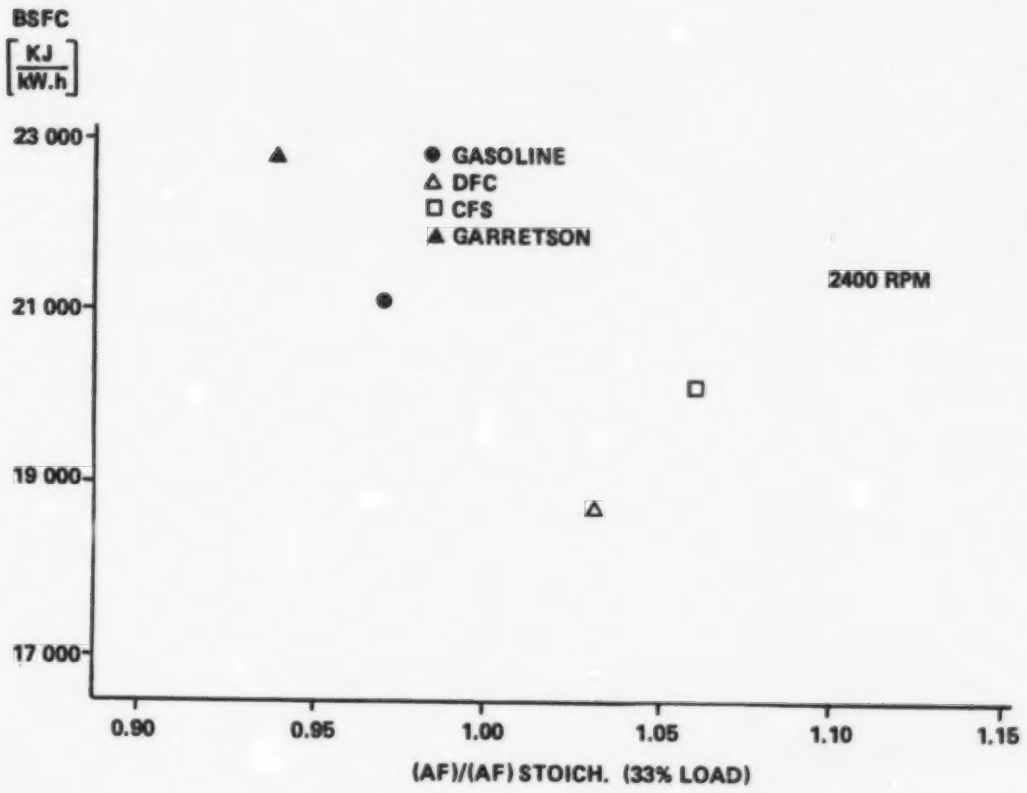


Figure 7/ Correlation Between Brake Specific Fuel Consumption and Air-Fuel Ratio at 33% Load (6.1 L V-8 Engine)

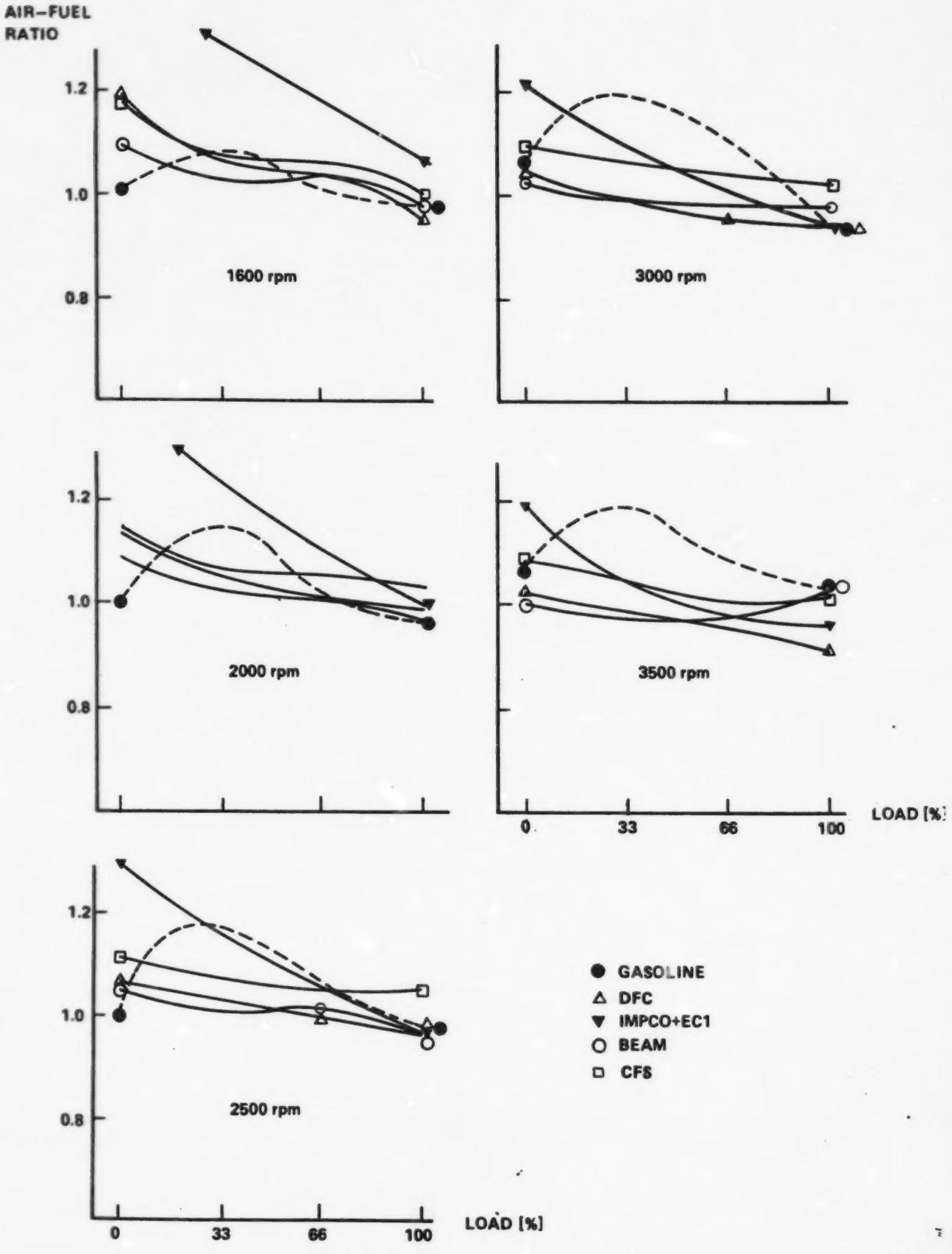


Figure 8/ Air-Fuel Equivalence Ratio (4.9 L I-6 Engine)

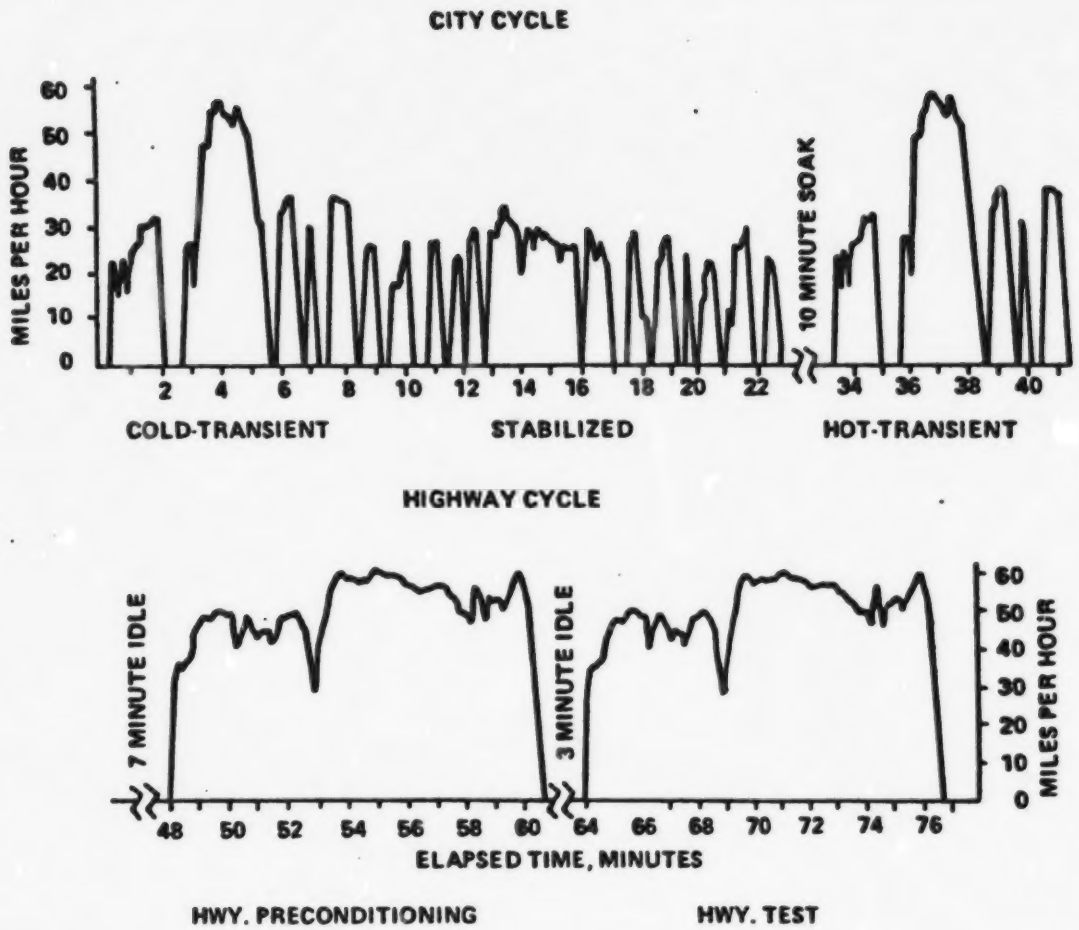


Figure 9/ City (Urban) and Highway Driving Cycles

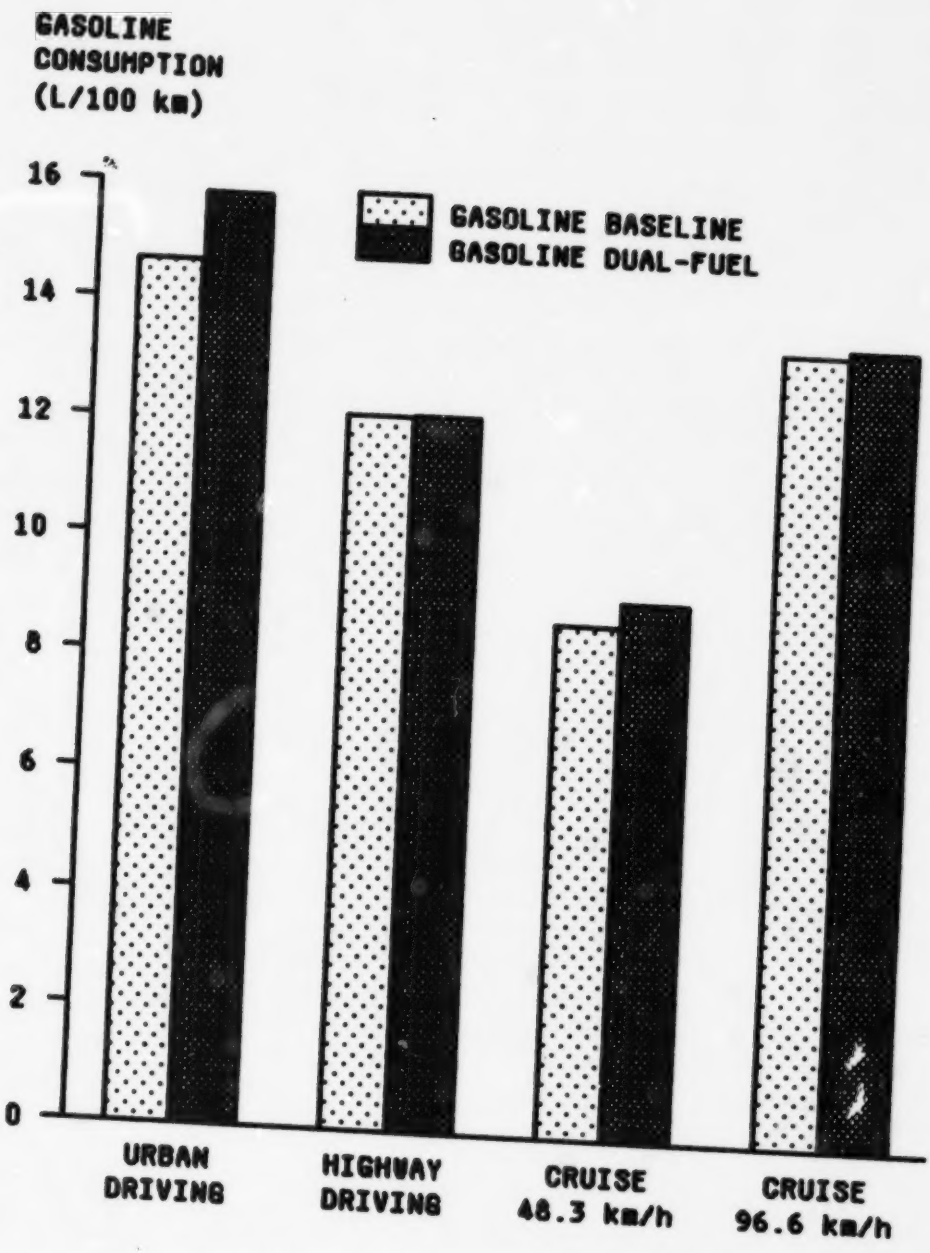


Figure 10/ Gasoline Consumption in the Baseline and Dual-Fuel Modes (Ford F-150 Pick-up Truck)

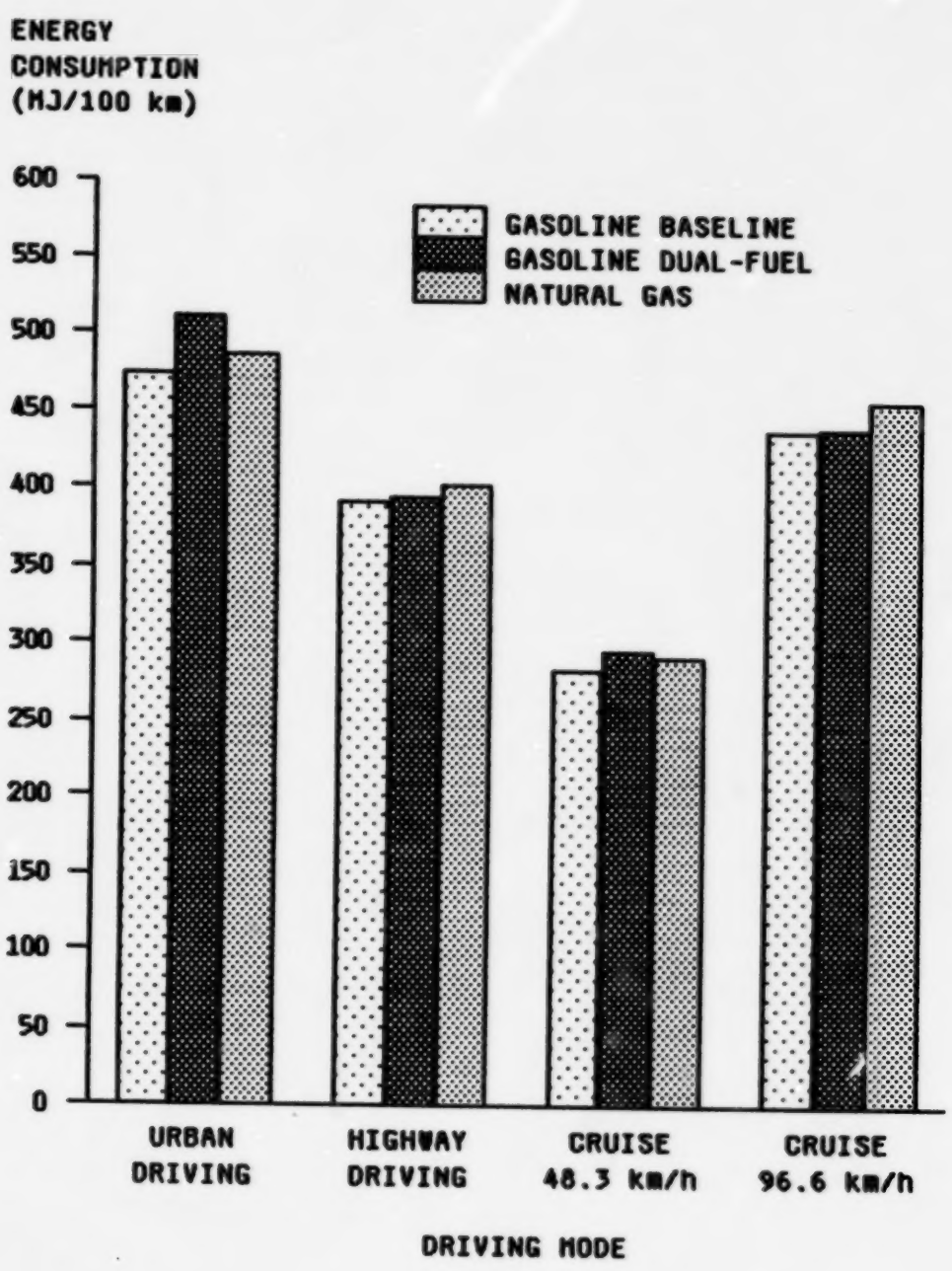


Figure 11/ Energy Consumption with Gasoline and Natural Gas (Ford F-150 Pick-up Truck)

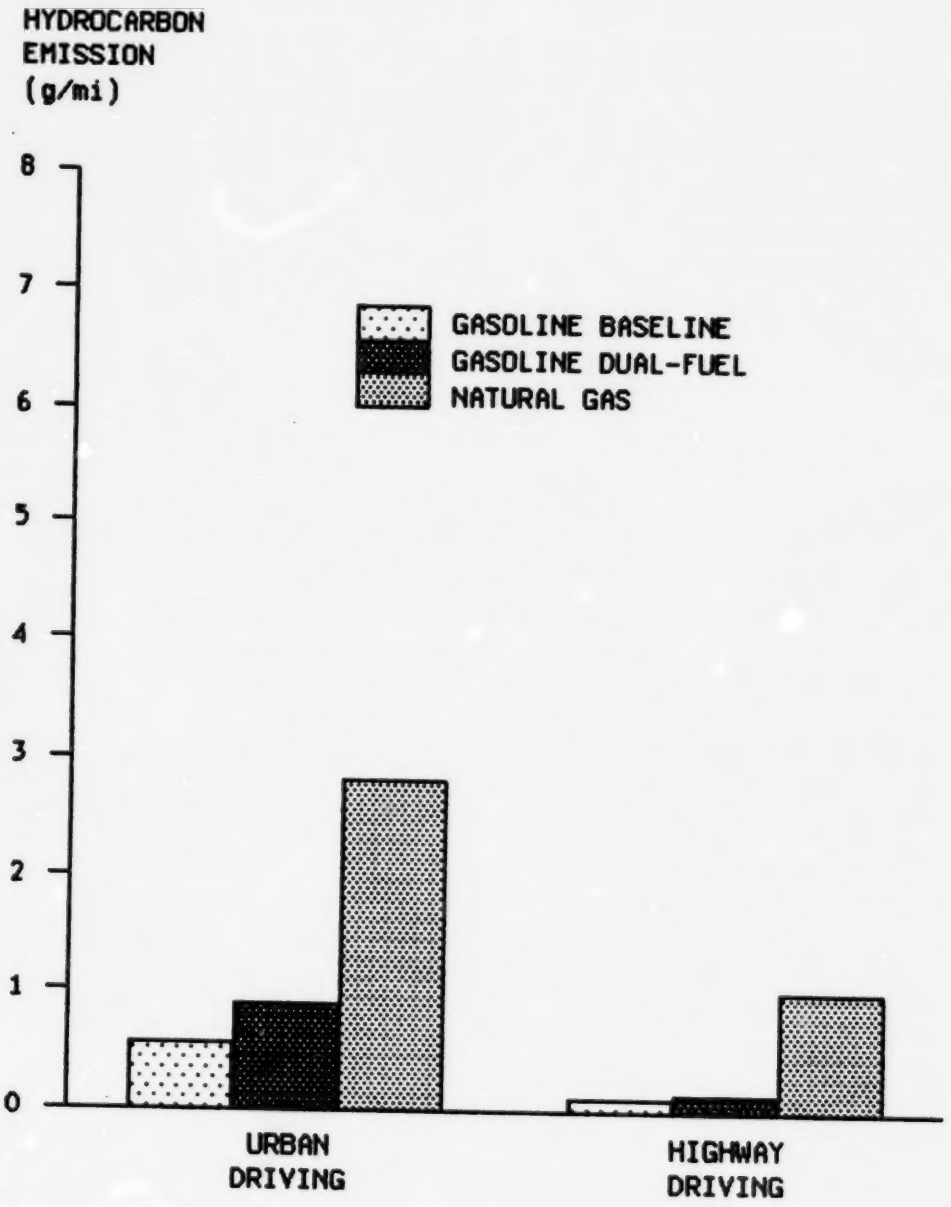


Figure 12/ Hydrocarbon Emissions with Gasoline and Natural Gas (Ford F-150 Pick-up Truck)

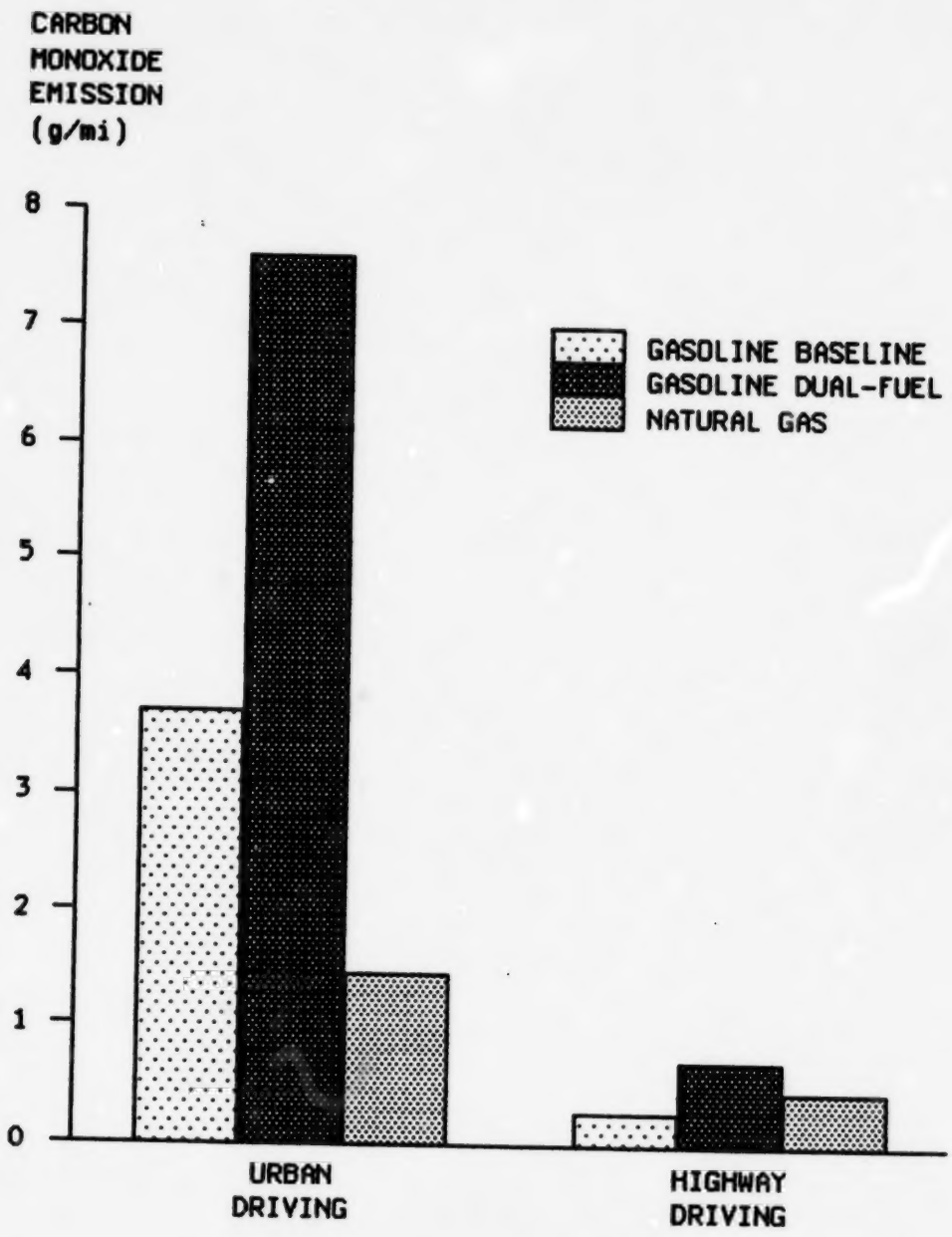


Figure 13/ Carbon Monoxide Emissions with Gasoline and Natural Gas (Ford F-150 Pick-up Truck)

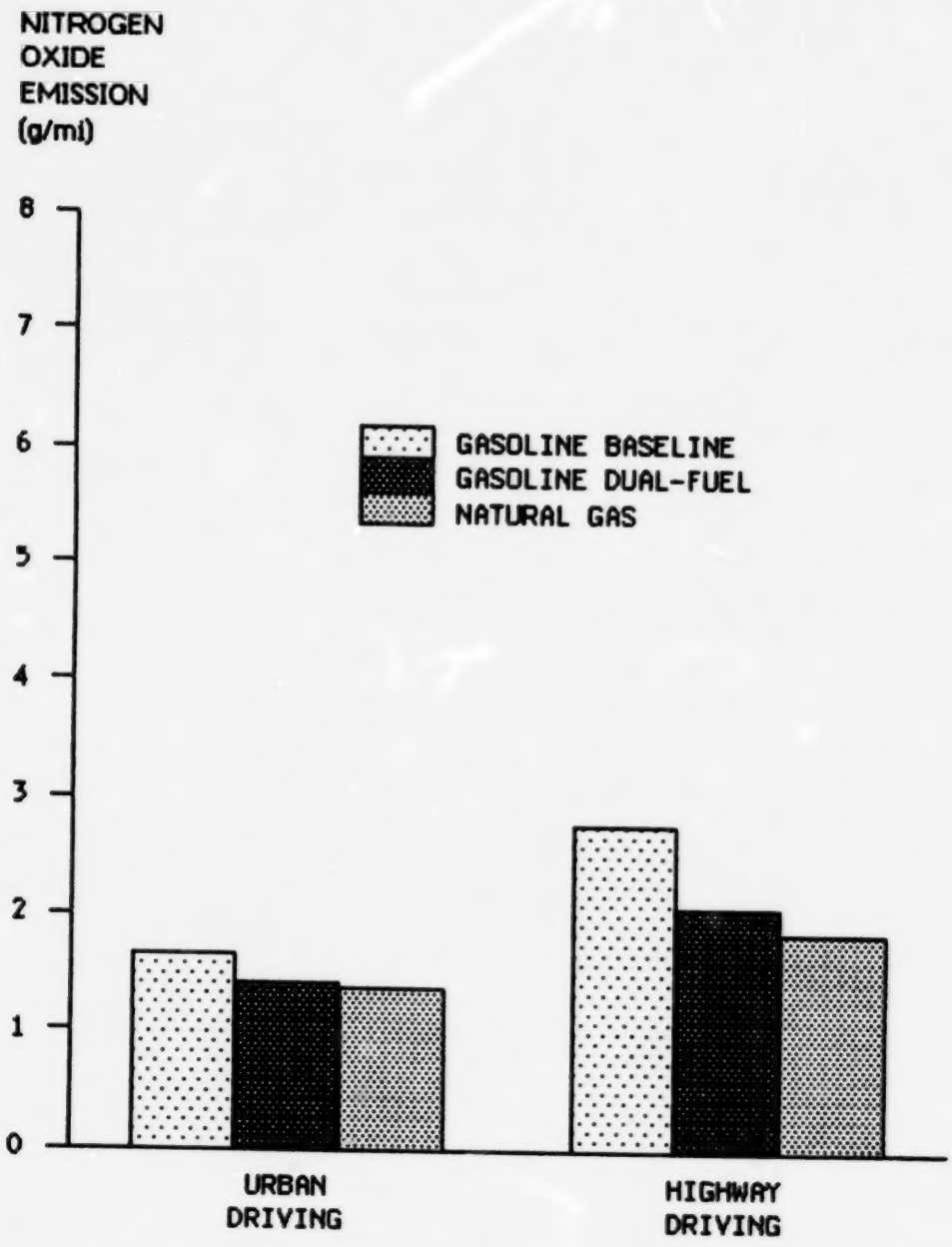


Figure 14/ Nitrogen Oxide Emissions with Gasoline and Natural Gas (Ford F-150 Pick-up Truck)

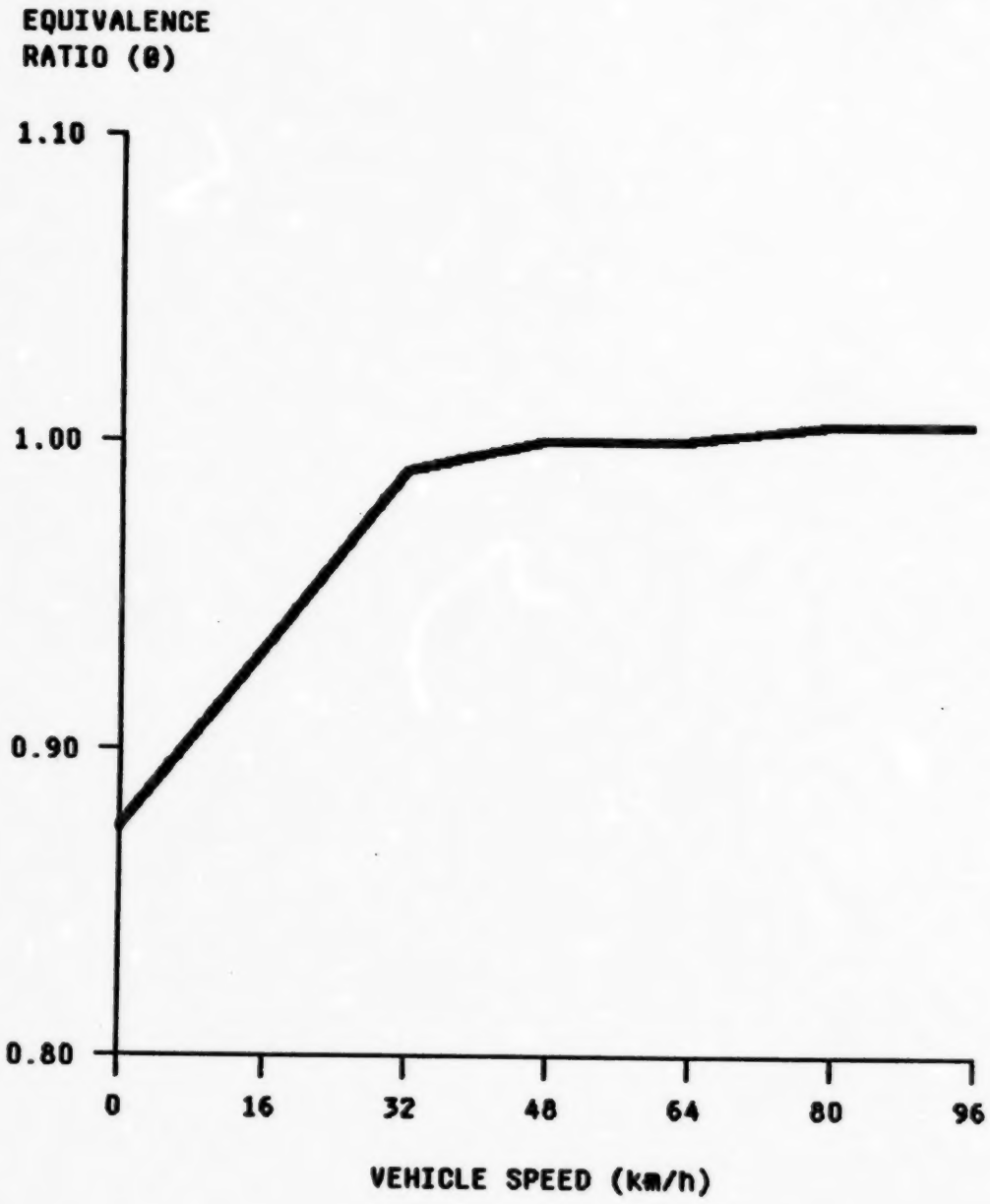


Figure 15/ Variation of the Air-Fuel Mixture Equivalence Ratio (θ) with Vehicle Speed (Baseline Gasoline Mode)

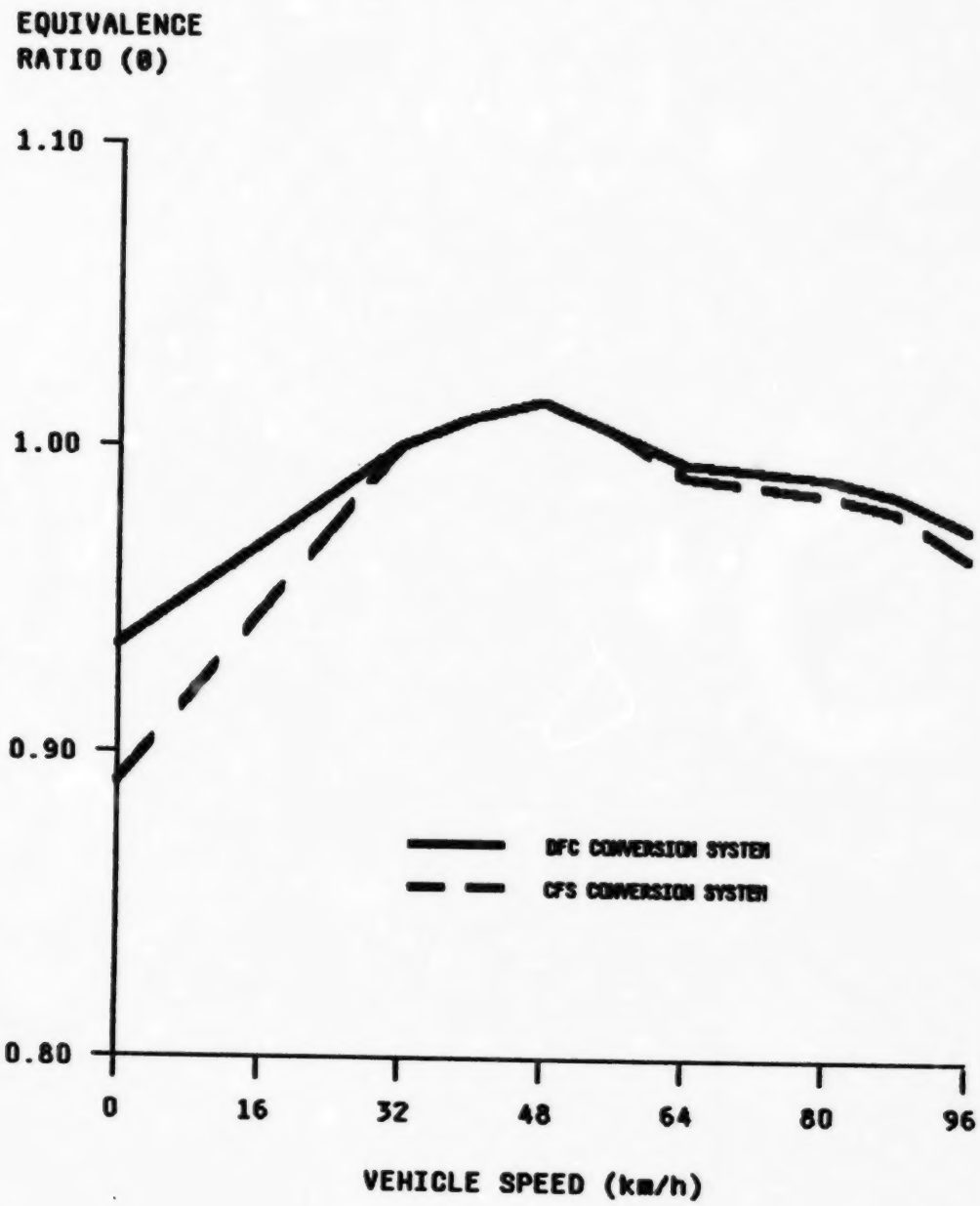


Figure 16/ Variation of the Air-Fuel Mixture Equivalence Ratio (θ) with Vehicle Speed (Dual-Fuel Vehicle in the Gasoline Mode)

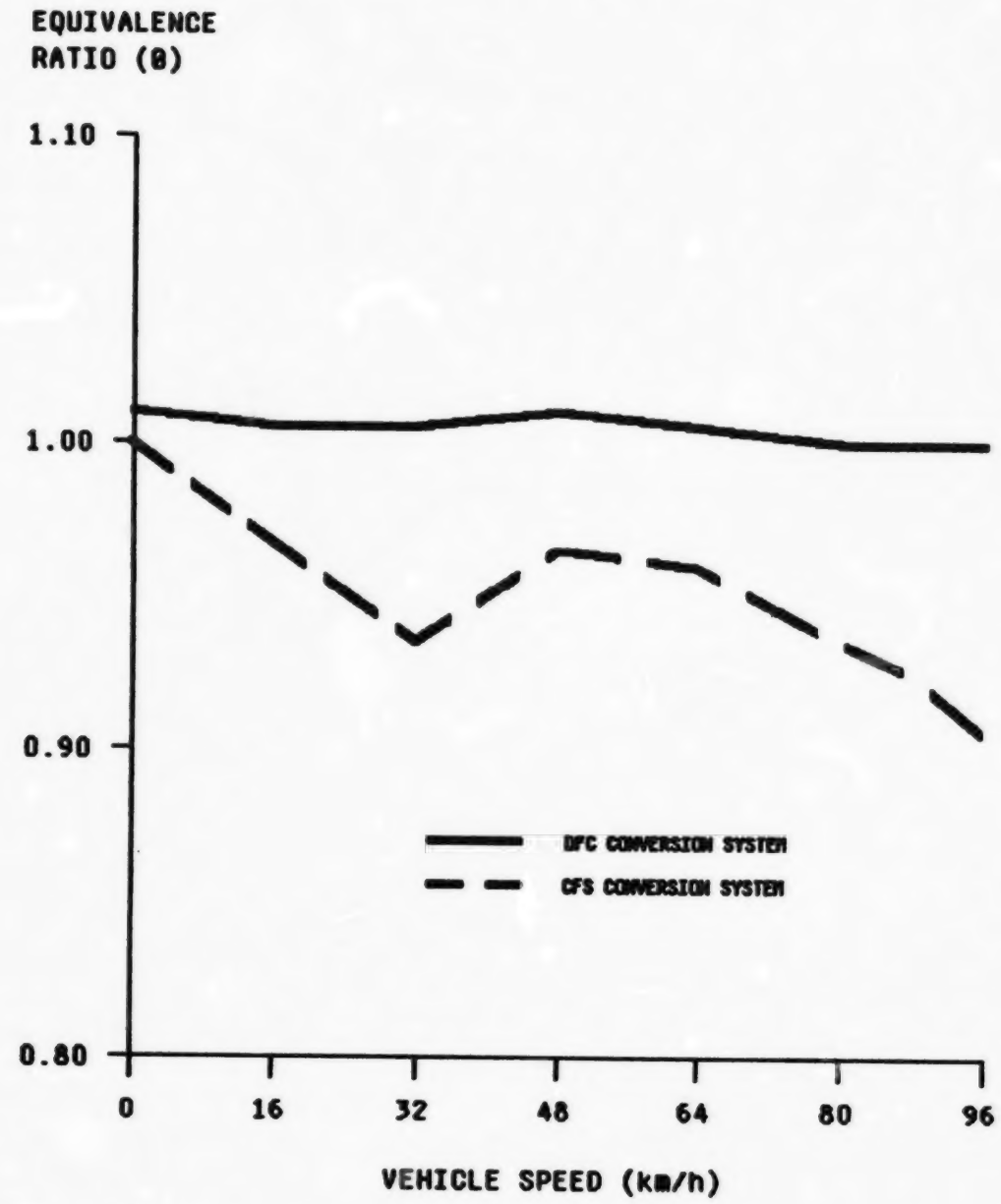


Figure 17/ Variation of the Air-Fuel Mixture Equivalence Ratio (θ) with Vehicle Speed (Dual-Fuel Vehicle in the Natural Gas Mode)

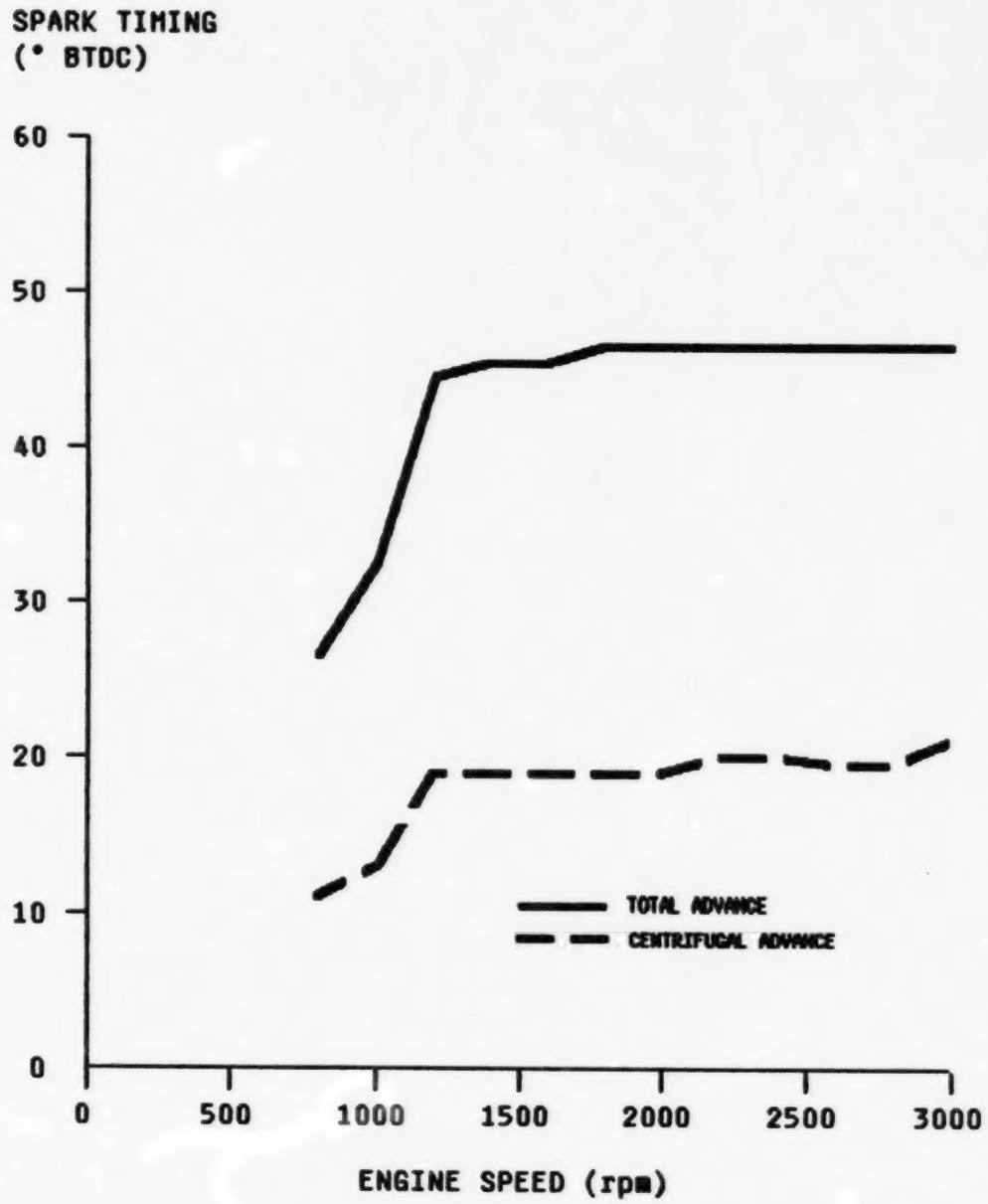


Figure 18/ Spark-Timing Curves of Baseline Gasoline Vehicle

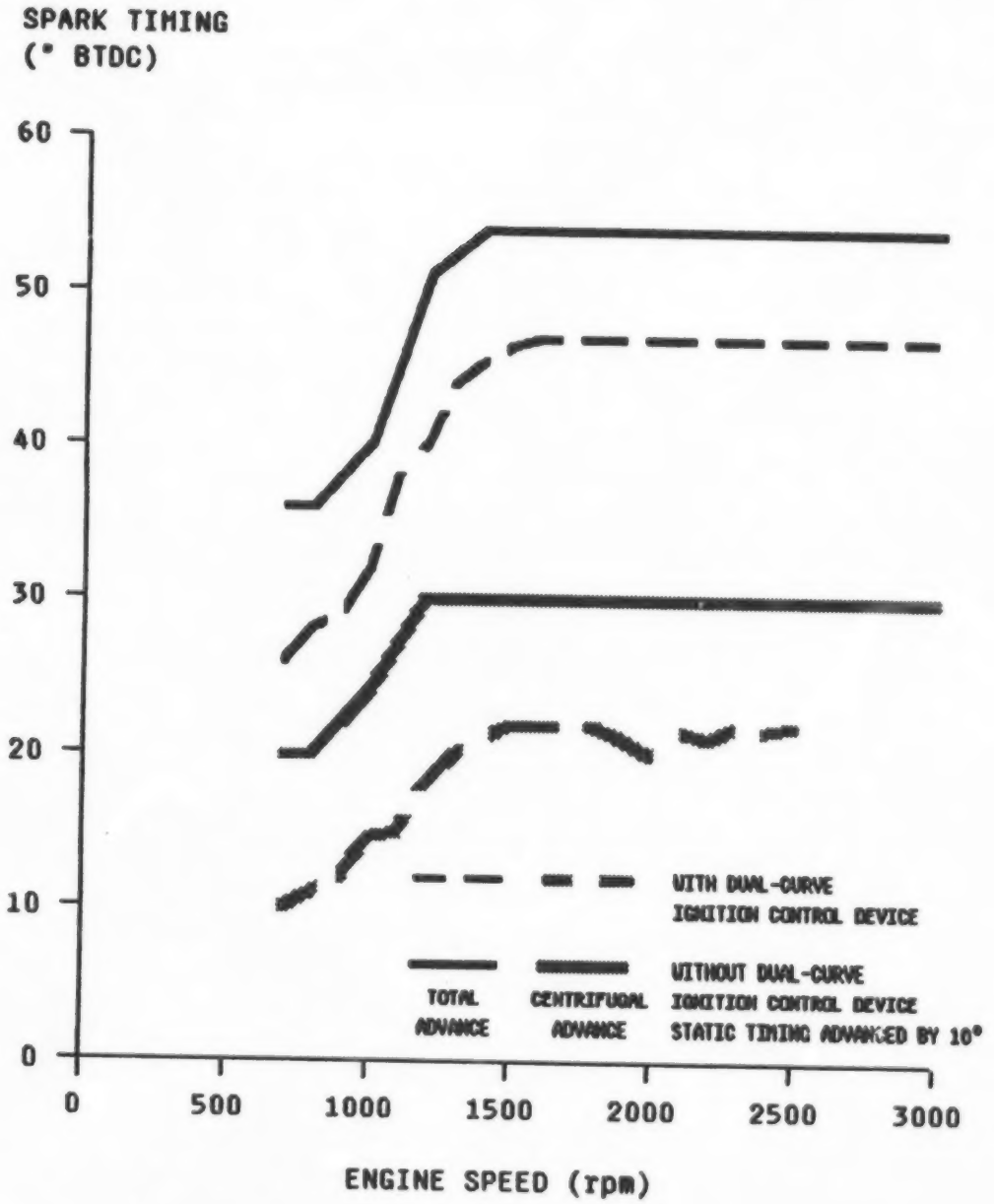


Figure 19/ Spark-Timing of Dual-Fuel Vehicle in the Gasoline Mode

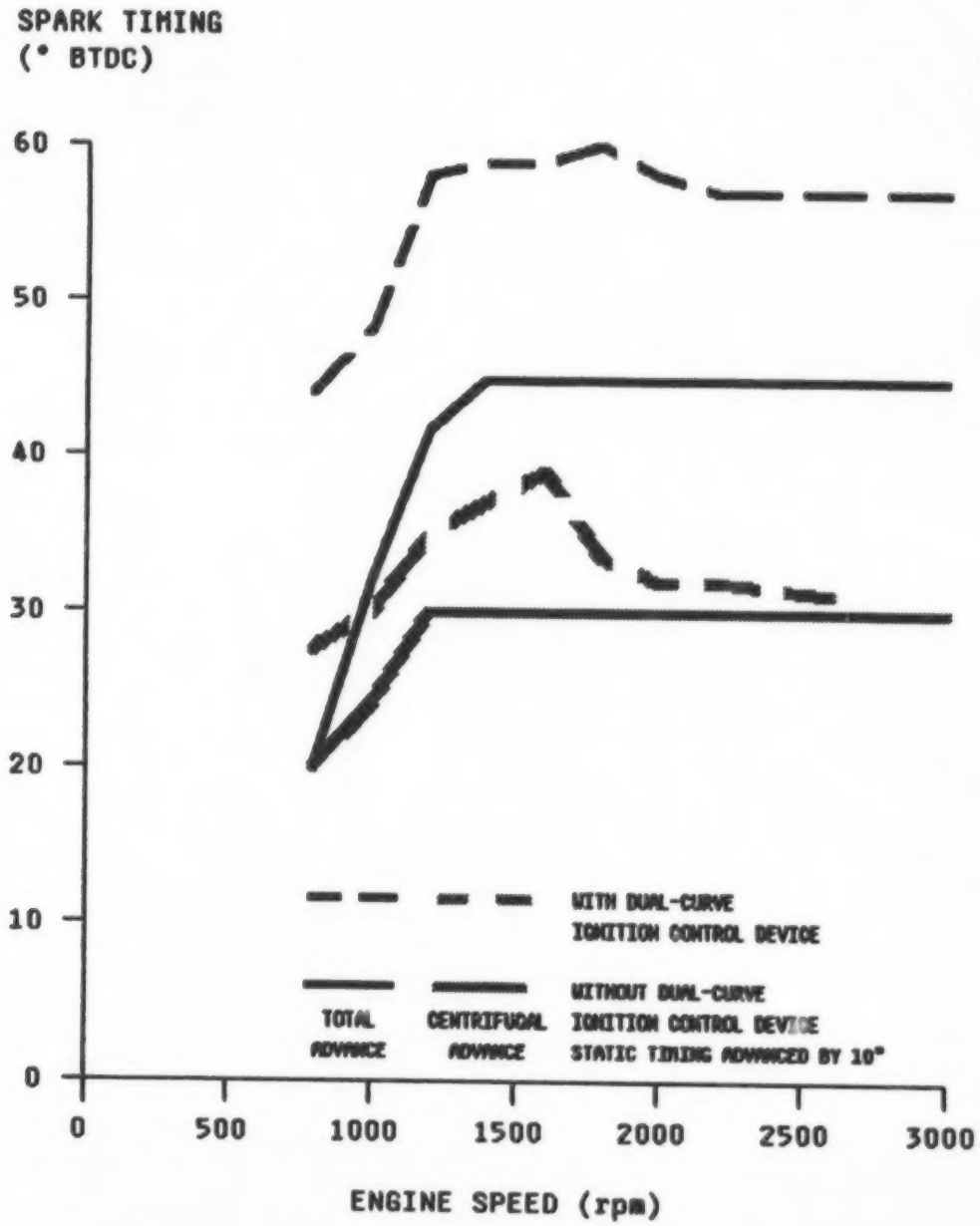


Figure 20/ Spark-Timing of Dual-Fuel Vehicle in the CNG Mode